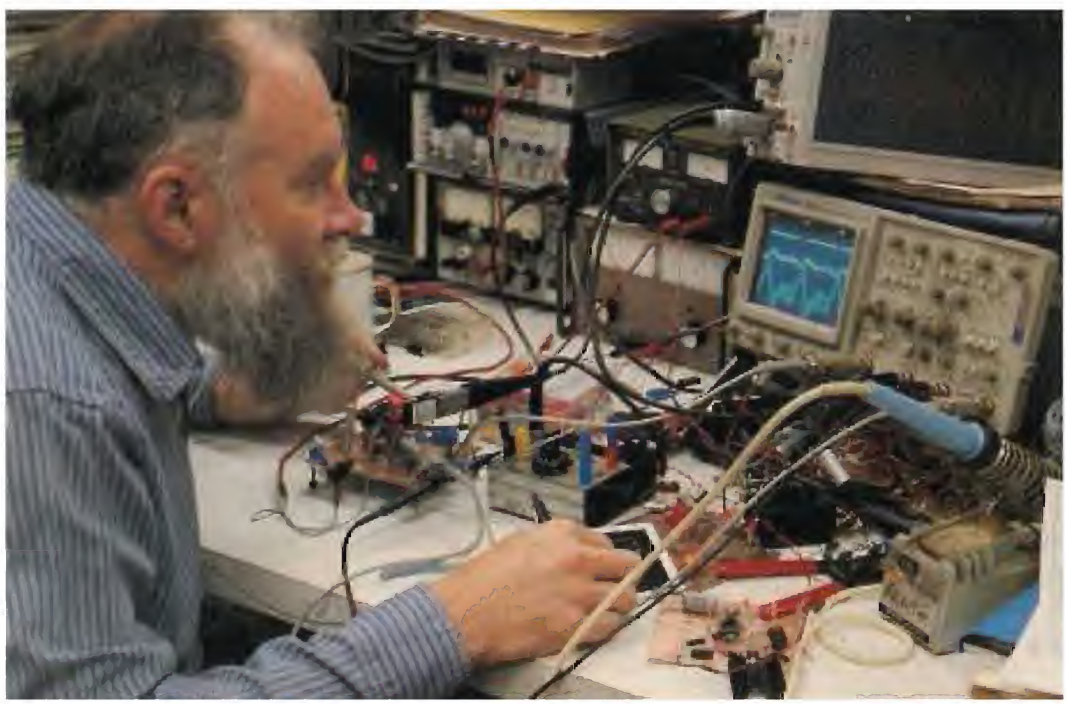
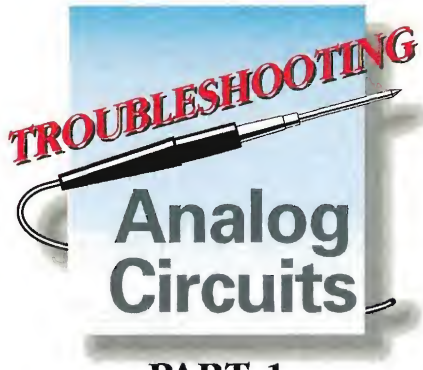
# *A Tribute to Bob Pease*

## Troubleshooting Analog Circuits



*(1989-1990 series of articles)*




**PART 1**

# Troubleshooting is more effective with the right philosophy

*In this first installment of a multipart series, one of the world's leading analog-circuit designers makes the case that a significant part of effective troubleshooting lies in the way that you think about the problem. The next installment will cover the equipment you should buy—and build—to help you diagnose problems, and future installments will illuminate some of the more subtle and elusive characteristics of passive and active components and the pc boards and cables that interconnect them.*

Robert A Pease, *National Semiconductor Corp*

If you recall that the most *boring* class in school was a philosophy class, and you think this article will be boring that way, well, WRONG. We are going to talk about the real world and examples of how we can recover from mistakes, goofs, and all the nasty problems the world tries to inflict on us. We are talking about Trouble with a capital T, and how to overcome it.

Here at National Semiconductor, we decided a couple of years ago to write a book about switching power supplies. Within the applications and design groups, nearly all of the engineers volunteered to write chapters, and I volunteered to do a chapter on troubleshooting. At present, the status of the book is unclear. But, the troubleshooting chapter is going strong, and EDN readers are the first to benefit.

Although I am probably not the world's best analog-circuit troubleshooter, I am fairly good; and I just happened to be the guy who sat down and put all these stories in writing. (Ed Note: *For a better insight into how Bob happened to tackle this assignment, see* ***box,*** *"Who is Bob Pease, anyway?"*) Furthermore, the techniques you need to troubleshoot a switching power supply apply, in general, to a lot of other analog circuits and may even be useful for some basic digital hardware. You don't have to build switchers to find this article useful—if you design or build any analog circuits, this article is for you.

Perhaps EDN readers who are more knowledgeable than I am about computers, microprocessors, and software will contact the editors about contributing articles on troubleshooting those types of products. If you don't have enough troubleshooting ideas to produce a full-length article but do have some good tips that you don't see in this series, send them to the Design Ideas editor at EDN. No doubt, EDN will print some of them. (Be sure to include a copy of the design entry blank included in each issue's Design Ideas section.)

Why are we interested in troubleshooting? Because even the best engineers take on projects whose requirements are so difficult and challenging that the

*Troubleshooting should resemble fencing more closely than it resembles wrestling.*

circuits don't work as expected—at least not the first time. I don't have data on switching regulators; but I read in an industry study that when disk drives are manufactured, the fraction that fails to function when power is first applied ranges from 20 to 70%. Of course, this fraction may occasionally fall as low as 1% and rise as high as 100%. But, on the average, production engineers and technicians must be prepared to repair 20, 40, or 60% of these complex units.

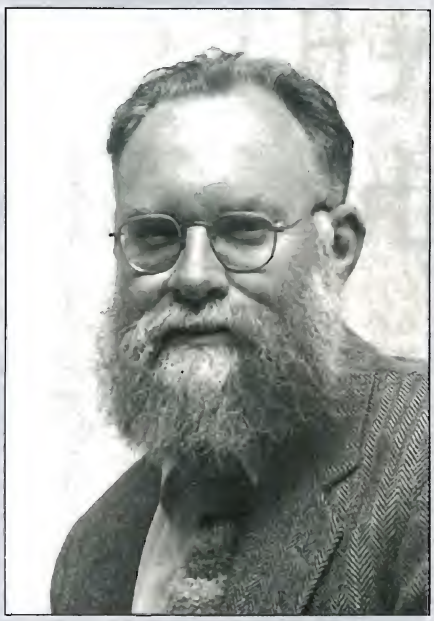
Switching-regulated power supplies can also be quite complex. If you manufacture them in batches of 100, you shouldn't be surprised to find some batches with 12 pieces that require troubleshooting and other batches that have 46 such pieces. The troubleshooting

## Who is Bob Pease, anyway?

For the record, Bob Pease is a senior scientist in industrial linear-IC design at National Semiconductor Corp in Santa Clara CA; he has worked at National since 1976. He is also one of the best-known analog-circuit designers in the world—he's been creating practical, producible analog products for fun (his) and profit (both his and his employers') and writing about analog topics for over a quarter of a century.

As you might expect, though, there's a lot more to Bob Pease than his impressive credentials. Following untrodden paths to discover where they lead is one of Bob's avocations. He's done it on foot, on skis, and on a bicycle—sometimes by himself and sometimes with his wife and two sons—mostly along abandoned railroad beds throughout the US. Aside from the peace and quiet and the thrill of the journey itself, the reward for these wanderings is observing vistas of America that few people have seen. The curiosity that motivates Bob's exploration of old railroad routes is reflected in many of his other activities both at and away from work.

For example, another of Bob's hobbies is designing voltage-to-frequency converters (VFCs). Most people who design VFCs do



it as part of a job. Although Bob sometimes designs VFCs for use in National products, he often does it just for fun and because he finds the activity educational and challenging. A while ago, on such a lark, he put together a VFC that used vacuum tubes. The device proved that the company where he spent the first 14 years of his career, George A Philbrick Researches, (now Teledyne-Philbrick of Dedham, MA) could have gone into the VFC business in 1953—eight years before Pease received his BSEE from MIT. Fifteen years after he designed it, one of Bob's first solid-state VFCs, the 4701, continues to sell well for Teledyne-Philbrick.

### Pease pontificates prolifically

Bob also loves to write—he clearly enjoys communicating to others the wisdom he has acquired through his work. He has published 46 magazine articles (not including this series) and holds eight patents. Bob takes great delight in seeing his ideas embodied in the work of others. For example, one of his proudest accomplishments is a seismic preamplifier that he designed for an aerospace company during his coffee break. After many years of service, the amplifier is still at work on the moon, amplifying and telemetering moonquakes.

National has taken advantage of Bob's penchant for providing ideas that others can use. In his role of senior scientist, Bob's responsibilities—besides designing voltage references and regulators, temperature sensors, and VFC ICs—include consulting with coworkers, fielding applications questions that have stumped other engineers, and reviewing colleagues' designs. In a similar vein, Bob is a long-time EDN contributing editor who reviews design-idea submissions in the analog area.—*Dan Strassberg*

***Peer review is often effective*** *for wringing problems out of designs. Here, the author gets his comeuppance from colleagues who are not as familiar with his circuit layout as he is.*

may, as you well know, be tough with a new product whose bugs haven't been worked out. But, it can be even tougher when the design is old and the parts it now uses aren't quite like the ones you once could buy. Troubleshooting can be tougher still when there is little documentation describing how the product is supposed to work and the designer isn't around anymore. If there's ever a time when troubleshooting isn't needed, it's just a temporary miracle.

**You might avoid troubleshooting . . . for a while**

And, what if you decide that troubleshooting isn't necessary? You may find that your first batch of products has only three or four failures, so you decide that you don't need to worry. The second batch has a 12% failure rate, and all of the rejects have the same symptoms as those of the first batch. The next three batches have failure rates of 23, 49, and 76%, respectively. When you finally take the time to study the problems, you will find that they would have been relatively easy to fix if only you had started a couple of months earlier. That's what Murphy's Law can do to you if you try to slough off your troubleshooting chores—we have all seen it happen.

If you have a bunch of analog circuits that you have to troubleshoot, well, why don't you just look up the troubleshooting procedures in a book? The question is excellent, and the answer is very simple: Almost nothing has been written about the troubleshooting of such circuits. The best write-up I have found is a couple pages in a book by Jiri Dostal **(Ref 1).** He gives some basic procedures for looking for trouble in a fairly straightforward little circuit: a voltage reference/regulator. As far as Dostal goes, he does quite well. But, he does not offer much advice, and there is much to explain beyond what he has written. Another book that has several pages about the philosophy of troubleshooting is by John I Smith **(Ref 2).** Smith explains some of the foibles of wishing you had designed a circuit correctly when you find that it doesn't work "right." What's missing, though, is general information.

**You'll probably use general-purpose test equipment**

What equipment can you buy for troubleshooting? I'll cover that subject in considerable detail in the next installment. For now, let me observe that if you have several million dollars worth of circuits to troubleshoot, you should consider buying a $100,000 tester. Of course, for that price you only get a machine at the low end of the line. And, after you buy the machine, you have to invest a lot of time in fixturing and software before it can help you. Yes, you can buy a $90 tester that helps locate short circuits on a pc board; but, in the price range between $90 and $100,000, there isn't a lot of specialized troubleshooting equipment available. If you want an oscilloscope, you have to buy a general-purpose oscilloscope; if you want a DVM, it will be a general-purpose DVM. Now, it's true that some scopes and some DVMs are more suitable for troubleshooting than others (and I will discuss the differences in the next part of this series), but, to a large extent, you have to depend on your wits.

Your wits: very handy to use—your wits—but, then what? One of my favorite quotes from Jiri Dostal's book says that troubleshooting should resemble fencing more closely than it resembles wrestling. When your troubleshooting efforts seem most like wrestling in the mud with an implacable opponent (or component), then you are probably not using the right approach. Do you have the right tools, and are you using them correctly? I'll discuss that in the next issue. Do you know how a failed component will affect your circuit, and do you know what the most likely failure modes are? I'll deal with components in subsequent installments. Ah, but do you know how to think about Trouble? That is today's main lesson.

One of the first things you might do is make a list of all the things that could be causing the problem. This idea can be good—up to a point. I am an aficionado of stories about steam engines, and this story comes from the book, *Master Builders of Steam* **(Ref 3).** A class of new 3-cylinder 4-6-0 (four little wheels in front

***The breadboard that launched a million chips,*** *including National's LM 131. Pease's breadboards are legendary.*

of the drive wheels, six drive wheels, no little wheels in back) steam engines had just been designed by British designer W A Stanier, and they were "perfect stinkers. They simply would not steam." So the engines' designers made a list of all the things that could go wrong and a list of all the things that could not be at fault; they set the second list aside.

The designers specified changes to be made to each new engine in hopes of solving the problem: "Teething troubles bring modifications, . . . and each engine can carry a different set of modifications." The manufacturing managers "shuddered as these modified drawings seemed to pour in from Derby (site of the design facility—the Drawing Office), continually upsetting progress in the works." (Lots of fun for the manufacturing guys, eh?)

In the end, the problem took a long time to find because it was on the list of "things that couldn't go wrong." Allow me to quote the deliciously horrifying words from the text: "Teething troubles always present these two difficulties: that many of the clues are very subjective and that the 'confidence trick' applies. By the latter I mean when a certain factor is exonerated as trouble-free based on a sound premise, and everyone therefore looks elsewhere for the trouble: whereas in fact, the premise is not sound and the exonerated factor is guilty. In Stanier's case this factor was low superheat. So convinced was he that a low degree of superheat was adequate that the important change to increased superheater area was delayed far longer than necessary. There were some very sound men in the Experimental Section of the Derby Loco Drawing Office at that time, but they were young . . . and their voice was only dimly heard. Some of their quite painstaking superheater test results were disbelieved." But, of course nothing like that ever happened to anybody you know—right?

Another thing you can do is ask advice only of "experts." After all, only an expert knows how to solve a difficult problem—right? Wrong! Sometimes, a major reason you can't find your problem is because you are too close to it—you are blinded by your familiarity. You may get excellent results by simply consulting one or two of your colleagues who are not as familiar with your design; they may make a good guess at a solution to your problem. Often a technician can make a wise (or lucky) guess as easily as can a savvy engineer. When that happens, be sure to remember who saved your neck. Some people are not just lucky—they may have a real knack for solving tricky problems, for finding clues, and for deducing what is causing the trouble. Friends like these can be more valuable than gold. (For more on clues, see **box,** "Learn to recognize clues.")

At National Semiconductor, we usually submit a newly designed circuit layout to a review by our peers. I invite everybody to try to win a Beverage of Their Choice by catching a real mistake in my circuit. It's fun because if I give away a few pitchers of brew, I get some of my dumb mistakes corrected—mistakes that I might not have found until a much later, more painful, and more expensive stage. Furthermore, we all get some education. And, you can never predict who will find the little mistakes or the occasional real killer mistake.

### You can make Murphy's Law work for you

Murphy's Law is quite likely to attack even our best designs: "If anything can go wrong, it will." But, I can make Murphy's Law work for me. For example, according to Murphy's Law, if I drive around with a fire extinguisher, I will make sure that I never have a fire in my car. When you first hear it, the idea sounds dumb. But, if I'm the kind of meticulous person who carries a fire extinguisher, I may also be neat and refuse to do the dumb things that permit fires to start. Similarly, when designing a circuit I leave extra safety margins in areas where I cannot surely predict how the circuit will perform. When I design a breadboard, I might tell the technician, "Leave 20% extra space for this part because I'm not sure that it will work without modifications. And, please leave extra space

around this resistor and this capacitor because I might have to change those values." When I design an IC, I leave little pads of metal at strategic points on the chip's surface, so that I can probe the critical nodes as easily as possible. To facilitate probing when working with 2-layer metal, I bring nodes up from the first metal through vias to the second metal. Sometimes I leave holes in my Vapox passivation to facilitate probing dice.

The subject of testability has often been addressed for large digital circuits, but the underlying ideas of design for testability are important regardless of the type of circuit you are designing. You can avoid a lot of trouble by thinking about what can go wrong and how to keep it from going wrong before the ensuing problems lunge at you. By planning for every possibility, you can profit from your awareness of Murphy's Law. Now, clearly, you won't think of *every* possibility. (Remember, it was something that *couldn't* go wrong that caused the problems with Stanier's locomotives.)

## Learn to recognize clues

There are four basic questions that you or I should ask when we are brought in to do troubleshooting on someone else's project:

- Did it *ever* work right?
- What are the symptoms that tell you it's not working right?
- When did it start working badly or stop working?
- What other symptoms showed up just before, just after, or at the same time as the failure?

As you can plainly see, the clues you get from the answers to these questions might easily solve the problem right away; if not, they may eventually get you out of the woods. So even if a failure occurs on your own project, you should ask these four questions—as explicitly as possible—of yourself or your technician or whoever was working on the project. Similarly, if your roommate called you to ask for a lift because the car had just quit in the middle of a freeway, you would ask whether anything else happened or if the car just died. If you're told that the headlights seemed to be getting dimmer and dimmer, that's a *clue.*

***The telephone** is sometimes a good troubleshooting tool; at other times, however, it is just another wretched part of the problem.*

When you ask these four questions, make sure to record the answers in a notebook. As an old test manager I used to work with would tell his technicians, "When you are taking data, if you see something funny, record the amount of funny." A few significant notes can save you hours of work. Clues are where you find them; they should be saved and savored.

Ask not only these questions but also any other questions suggested by the answers. For example, a neophyte product engineer will sometimes come to see me with a batch of ICs that have a terrible yield at some particular test. I'll ask if the parts failed any other tests, and I'll hear that nobody knows because the tester doesn't continue to test a part after it detects a failure. A more experienced engineer would have already retested the devices in the RUN ALL TESTS mode.

Likewise, if *you* are asking another person for advice, you should have all the facts laid out straight—at least in your head—so that you can be clear and not add to the confusion. I've worked with a few people who tell me one thing and a minute later start telling me the opposite. Nothing makes me lose my temper faster! Nobody can help you troubleshoot effectively if you aren't sure whether the circuit is running from +12V or ±12V and you start making contradictory statements.

And, if I ask when the device started working badly, *don't* tell me, "At 3:25 PM." I'm looking for clues, such as, "About two minutes after I put it in the 125°C oven," or, "Just after I connected the 4-Ω load." So just as we can all learn a little more about troubleshooting, we can all learn to watch for the clues that are invaluable for fault diagnosis.

*It is important to get the paperwork scrupulously correct, or the alligators will surely circle back to vex you again.*

***A large collection of used components** in good condition, such as the group of capacitors shown here, forms one part of an experienced analog troubleshooter's hardware armamentarium.*

But, a little forethought can certainly minimize the number of problems you have to deal with.

Recently, we had so many nagging little troubles with band-gap reference circuits at National, that I decided (unilaterally) to declare myself, "Czar of Band Gaps." The main rules were that (**a**) all successful band-gap circuits should be registered with the Czar so that we could keep a log book of successful circuits; (**b**) all unsuccessful circuits, their reasons for failure, and the fixes for the failures should likewise be logged in with the Czar so that we could avoid repeating old mistakes; and (**c**) all new circuits should be submitted to the Czar to allow him to spot any old errors. So far, we think we've found over 50% of the possible errors, and we're gaining. In addition, we have added Czars for start-up circuits and for trim circuits, and we are considering other czardoms. It's a bit of a game, but it's also a serious business to use a game to try to prevent expensive errors.

I haven't always been a good troubleshooter, but my "baptism of fire" occurred quite a few years ago. I had designed a group of modular data converters. We had to ship 525 of them, and some foolish person had bought only 535 pc boards. When less than half of the units worked, I found myself in the troubleshooting business because nobody else could imagine how to repair them. I discovered that I needed my best-triggering scope and my best DVM. I burned a lot of midnight oil. I got half-a-dozen copies each of the schematic and the board layout. I scribbled notes on them—of what the dc voltages ought to be, what the correct ac waveforms looked like, and where I could best probe the key waveforms. I made little lists of, "If this frequency is twice as fast as normal, look for Q47 to be damaged, but if the frequency is $\frac{1}{10}$ normal, look for a short on bus B." I learned where to look for solder shorts, hairline opens, cold-soldered joints, and intermittents. I diagnosed the problems and sent each unit back for repair with a neat label of what to change. When they came back, did they work? Some did—and some still had another level or two of problems. That's the Onion Syndrome: You peel off one layer, and you cry; you peel off another layer and cry some more . . . By the time I was done, I had fixed all but four of the units, and I had gotten myself one hell of a good education about troubleshooting.

After I found a spot of trouble, what did I do about it? First of all, I made some notes to make sure that the problem really was fixed when the offending part was changed. Then I sent the units to a *good, neat* technician who did precise repair work—much better than a slob like me would do. Lastly, I sent memos to the manufacturing and QC departments to make sure that the types of parts that had proven troublesome were not used again, and I confirmed the changes with ECOs (engineering change orders). It is important to get the paperwork scrupulously correct, or the alligators will surely circle back to vex you again.

I once heard of a similar situation where an insidious problem was causing nasty reliability problems with a

*Clues are where you find them; they should be saved and savored.*

batch of modules. The technician had struggled to find the solution for days. Finally, when the technician went out for lunch, the design engineer went to work on the problem. When the technician came back from lunch, the designer told him, "I found the problem; it's a mismatch between Q17 and R18. Write up the ECO, and when I get back from lunch I'll sign it." Unfortunately, the good rapport between the engineer and the technician broke down: there was some miscommunication. The technician got confused and wrote up the ECO with an incorrect version of what should be changed. When the engineer came back from lunch, he initialled the ECO without really reading it and left for a two-week vacation.

When he came back, the modules had all been "fixed," potted, and shipped, and were starting to fail out in the field. A check of the ECO revealed the mistake—too late. The company went bankrupt. It's a true story and a painful one. Don't get sloppy with your paperwork; don't let it happen to you.

**Troubleshooting by phone—a tough challenge**

These days, I do quite a bit of troubleshooting by telephone. When my phone rings, I never know if a customer will be asking for simple information or submitting a routine application problem, a tough problem, or an insoluble problem. Often I can give advice just off the top of my head because I know how to fix what is wrong. At other times, I have to study a while before I call back. Sometimes, the circuit is so complicated that I tell the customer to mail or transmit the schematic to me. On rare occasions, the situation is so hard to analyze that I tell the customer to put the circuit in a box with the schematic and a list of the symptoms and ship it to me.

Sometimes the problem is just a misapplication. Sometimes parts have been blown out and I have to guess what situation caused the overstress. Here's an example: In June, a manufacturer of dental equipment complained of an unacceptable failure rate on LM317 regulators. After a good deal of discussion, I asked, "Where did these failures occur?" Answer: North Dakota. "When did they start to occur?" Answer: In February. I put two and two together and realized that the climate in a dentist's office in North Dakota in February is about as dry as it can be and is conducive to very high electrostatic potentials. The LM317 is normally safe against electrostatic potentials as high as 3 or 4 kV, but walking across a carpeted floor in North Dakota in February can generate even higher voltages. To make matters worse, the speed-control rheostat for this dental instrument was right out in the handle. The wiper and one end of the rheostat were wired directly to the LM317's ADJUST pin; the other end of the rheostat was connected to ground by way of a 1-kΩ resistor located near the IC.

The problem was easily solved by placing the resistor in series with the IC's ADJUST pin and relocating it to the instrument's handle. By moving the resistor and connecting the rheostat wiper to ground, much less current would take the path to the ADJUST pin and the diffused resistors on the chip would not be damaged or zapped by the current surges.

A similar situation occurs when you get a complaint from Boston in June, "Your op amps don't meet spec for bias current." The solution is surprisingly simple: Usually a good scrub with soap and water works better than any other solvent to clean off the residual contaminants that cause leakage under humid conditions.

**When computers replace troubleshooters, look out**

Now, let's think—what *needs* troubleshooting? Circuits? Television receivers? Cars? People? Surely doctors have a lot of troubleshooting to do—they listen to symptoms and try to figure out the solution. What is the natural temptation? Letting a computer do all the work! After all, a computer is quite good at listening to complaints and symptoms, asking wise questions, and proposing a wise diagnosis. Such a computer system is called an expert system—part of the general field of artificial intelligence. But, I am still in favor of *genuine* intelligence.

I won't argue that the computer isn't a natural for this job; it will probably be cost effective, and it won't be absent minded. But, I am definitely nervous because if computers do all the routine work, soon there will be nobody left to do the thinking when the computer gives up and admits it is stumped. I sure hope we don't let the computers leave the smart troubleshooting people without jobs, whether the object is circuits or people.

My concern is shared by Dr. Nicholas Lembo, the author of a study on how physicians make diagnoses, which was published in the *New England Journal of Medicine*. He recently told the *Los Angeles Times*, "With the advent of all the new technology, physicians aren't all that much interested (in bedside medicine) because they can order a $300 to $400 test to tell them something they could have found by listening." An editorial accompanying the study commented sadly:

"The present trend . . . may soon leave us with a whole new generation of young physicians who have no confidence in their own ability to make worthwhile bedside diagnoses." Troubleshooting is still an art, and it is important to encourage those artists.

**No problems? No problem . . . just wait**

Now, let's skip ahead and presume we have all the necessary tools and the right receptive attitude. What else do we need? What is the last missing ingredient? That reminds me of the little girl in Sunday School who was asked what you have to do to obtain forgiveness of sin. She shyly replied, "First you have to sin." So, to do troubleshooting, first you have to have some trouble. But, that's usually not a problem; just wait a few hours, and you'll have plenty. Murphy's Law implies that if you are not prepared for trouble, you will get a lot of it. Conversely, if you have done all your homework, you may avoid most of the possible trouble.

I've tried to give you some insights on the philosophy of how to troubleshoot. Don't believe that you can get help on a given problem from only one specific person. In any particular case, you can't predict who might provide the solution. Conversely, when your buddy is in trouble and needs help, give it a try—you could turn out to be a hero. And, even if you don't guess correctly, when you do find out what the solution is, you'll have added another tool to your bag of tricks. EDN

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Article Interest Quotient (Circle One)
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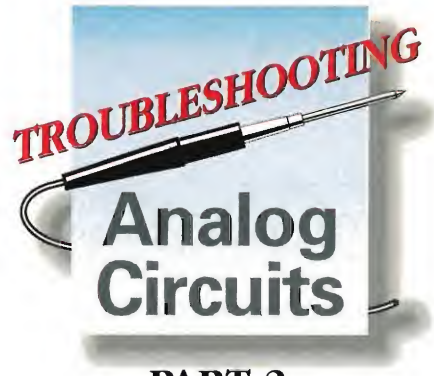


**PART 2**

# The right equipment is essential for effective troubleshooting

*As discussed in part 1 of this multipart series, the most important thing you need for effective troubleshooting is your wits. In addition to those, however, you'll normally want to have some equipment. This second installment itemizes the equipment that is necessary for most general troubleshooting tasks; some you can buy off-the-shelf, and some you can build yourself.*

Robert A Pease, *National Semiconductor Corp*

Before you begin your troubleshooting task, know that the equipment you use has a direct bearing on the time and effort you must spend to get the job done. Also know that the equipment you need to do a good job depends on the kind of circuit or product you are working on. For example, a DVM may be unnecessary for troubleshooting some problems in digital logic. And, the availability and accessability of equipment may present certain obstacles. If you only have a mediocre oscilloscope and your company can't go out and buy or rent a fancy full-featured scope, then you will have to make do.

If you lack a piece of equipment, be aware that you are going into battle with inadequate tools; certain clues may take you much longer than necessary to spot. In many cases when you spent too much time finding one small problem, the time was wasted because you were foolish or were unaware of a particular troubleshooting technique; but, in other cases, the time was wasted because of the lack of a particular piece of equipment. It's important for you to recognize this last-mentioned situation. Learning when you're wasting time because you lack the proper equipment is part of your education as a troubleshooter.

In addition to the proper tools, you also need to have a full understanding of how both your circuit and your equipment are supposed to work. I'm sure you've seen engineers or technicians work for many fruitless hours on a problem and then, when they finally find the solution, say, "Oh, I didn't know it was supposed to work that way." You can avoid this scenario by using equipment that you are comfortable and familiar with.

The following equipment is essential for most analog-circuit troubleshooting tasks. This list can serve as a guide to both those setting up a lab and those who just want to make sure that they have everything they need.

1 A dual-trace oscilloscope. It's best to have one with a sensitivity of 1 or 2 mV/cm and a bandwidth of at least 100 MHz. Even when you are working with slow op amps, a wide-bandwidth scope is important

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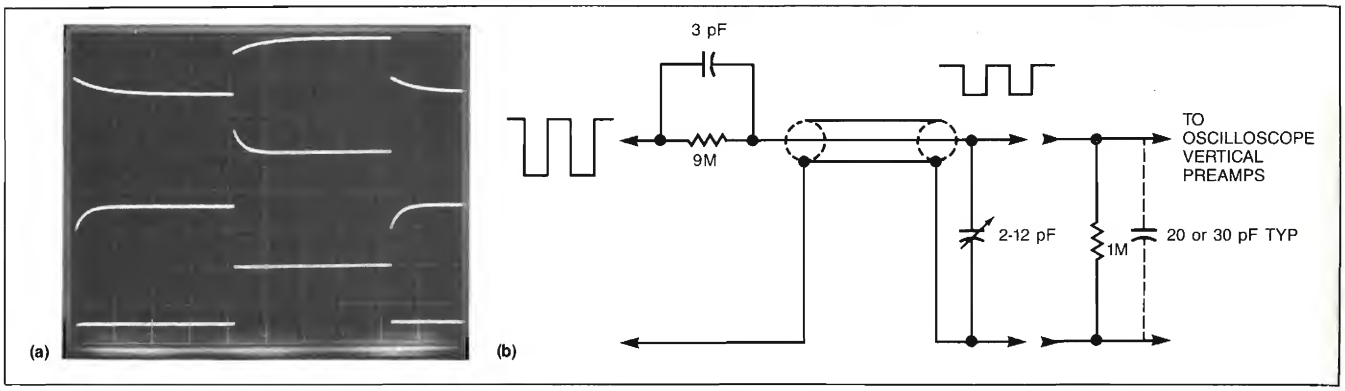



***Fig 1—If an amplifier or a comparator is supposed to produce a square wave*** *but the waveform looks like* ***a*** *trace A or B, how long should it take you to find the problem? No time at all. Just turn the screw that adjusts the 10x probe's compensation, so the probe's response is flat at all frequencies (****a****, trace C). The schematic diagram of a 10x oscilloscope probe is shown in* ***b****.*

because some transistors in "slow" applications can oscillate at 80 or 160 MHz, and you should be able to see these little screams. Of course, when working with fast circuits, you may need to commandeer the lab's fastest scope to look for glitches. Sometimes a peak-to-peak automatic triggering mode is helpful. Be sure you know how all the controls work, so you don't waste much time with setup and false-triggering problems.

**2** Two or three scope probes. They should be in good condition and have suitable hooks or points. Switchable 1x/10x probes are useful for looking at both large and very small signals. You should be aware that 1x probes only have a 16- or 20-MHz bandwidth, even when used with a 100-MHz scope. When you use 10x probes, be sure to adjust the capacitive compensation of the probe by using the square-wave calibrator. Failure to do so can be a terrible time-wasting source of trouble (**Fig 1**). Ideally, you'll want three probes at your disposal, so that you can have one for the trigger input and one for each channel. For general-purpose troubleshooting, the probes should have a long ground wire, but for high-speed waveforms you'll need to change to a short ground wire (**Fig 2**).

In some high-impedance circuits, even a 10x probe's capacitance, which is typically 9 to 15 pF, may be unacceptable. For these circuits, you can buy an active probe with a lower input capacitance of 1.5 to 3 pF ($395 to $1800), or you can build your own (**Fig 3**).

**3** An analog-storage oscilloscope. Such a scope can be extremely useful, especially when you are searching for an intermittent or evanescent signal. The scope can trigger off an event that may occur only rarely and can store that event and the events that follow it. Some storage scopes are balky or tricky to

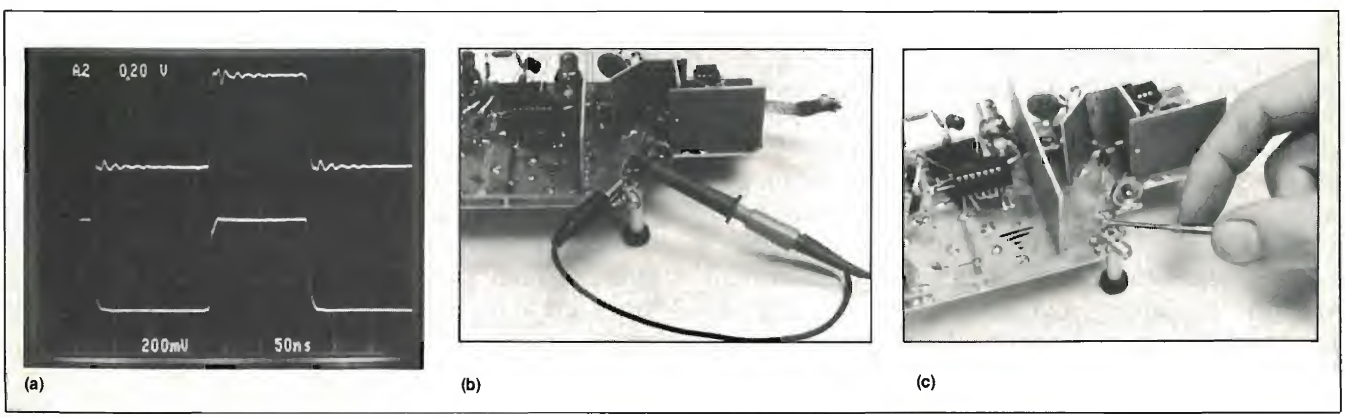



***Fig 2—When a fast square wave*** *is supposed to be clean and fast-settling but looks like* ***a****, trace A, don't repair the square-wave generator—just throw away the probe's 6-in. ground lead* ***(b)****. If you ground the probe directly at the ground point near the tip* ***(c)*** *(special attachments that bring the ground out conveniently are available), your waveforms will improve (****a****, trace B).*

apply, but it's often worthwhile to expend the effort to learn how to use them.

Digital-storage oscilloscopes (DSOs) let you do the same type of triggering and event storage as do the analog type, and some can display events that precede the trigger. They are sampled-data systems, however, so you must be sure to apply them correctly (**Ref 1**). Once you learn how to use them, though, you'll appreciate the special features they offer, such as bright CRT displays, automatic pulse-parameter measurements, and the ability to obtain plots of waveforms.

4 A digital voltmeter (DVM). Choose one with at least five digits of resolution, such as the HP3455, the HP3456, the Fluke 8810A, and the Fluke 8842A. Be sure you can lock out the autorange feature, so that the unit can achieve its highest accuracy and speed. Otherwise, you'll be wasting time while the DVM autoranges. For many analog circuits, it's important to have a high-impedance (>10,000-MΩ) input that can handle 15 to 20V; the four DVMs mentioned above have this feature. There are many other fine DVMs that have 10-MΩ inputs above 2 or 3V; and, if a 10-MΩ input impedance is not a problem, they are acceptable.

The most important reason to use a high-input-impedance DVM is because sometimes it's necessary to put 33-kΩ or 100-kΩ resistors in series with the probe, right near the circuit-under-test, to prevent the DVM's input capacitance from causing the circuit to oscillate. If you're using a DVM with a 10-MΩ input impedance and you have a 100-kΩ resistor in series with the probe, the DVM's measurements would lose 1% of their accuracy. Fortunately, many good DVMs have less than 500 pA of input current, which would cause less than 50 μV of error in the 100-kΩ-load case.

A high-resolution DVM lets you detect 100- to 200-μV deviations in an 11V signal. You can best spot many semiconductor problems by finding these minor changes. A 4-digit DVM is a relatively poor tool; although, in some cases, you can detect small voltage changes if you refer the DVM's "low," or ground, side to the 10V bus. Then, with the DVM in the 1V range, you can spot small deviations in an 11V signal. This measurement is more awkward and inconvenient than a ground-referenced measurement with a higher resolution meter would be, and this method can cause other problems as well. For instance, you can end up injecting noise generated by the DVM's A/D converter into the sensitive 10V reference, thereby adversely affecting the performance of other circuits.

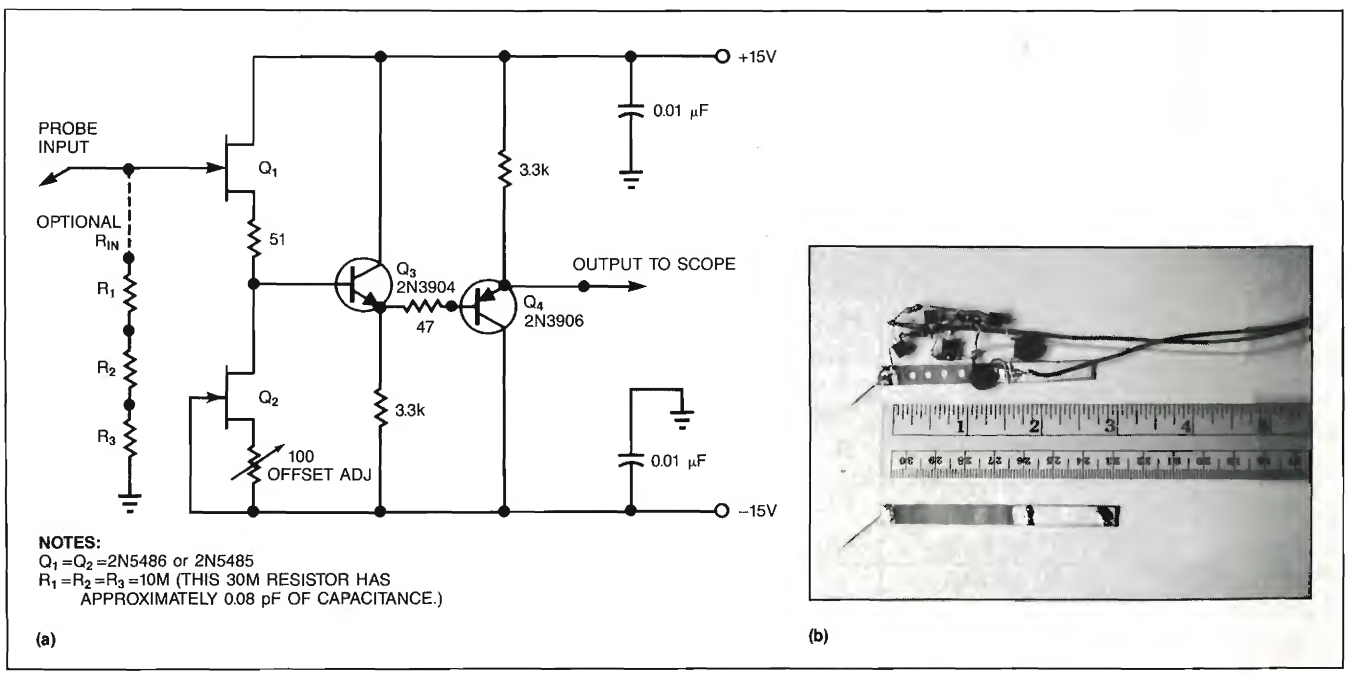



***Fig 3—This probe circuit's input impedance** is $10^{11}\Omega$ in parallel with 0.29 pF **(a)**. Optimized for its impedance characteristics and not its frequency response, the probe's bandwidth and slew rate are 90 MHz and 300V/μsec, respectively. If the lack of physical rigidity of the TO-92 packaged FET makes it difficult to use as a probe, a piece of 1/16-in. glass epoxy board with the copper peeled off will add rigidity with only 0.08 pF of additional capacitance. The layout shown in **b** adds only 0.06 pF to the input impedance.*

*If you lack a piece of equipment, be aware that you are going into battle with inadequate tools.*

5 Auxiliary meters. It may look silly to see a test setup consisting of two good DVM's, two little 3-digit DVMs monitoring a couple of voltage supplies, a couple more 3-digit DVMs monitoring current drain, and an analog meter monitoring something else. But, if you don't know exactly what you're looking for and you can borrow equipment, using lots of meters is an excellent way to attack a problem—even if you do have to wait until 5:15 pm to borrow all that equipment.

When is an analog voltmeter better than a DVM? Well, the analog voltmeter usually has inferior accuracy and resolution, but when you watch an ordinary analog voltmeter your eye can detect a trend or rate-of-change that may be hard to spot on a DVM, especially in the presence of noise or jitter. As an example, if you suddenly connect an ordinary volt-ohmmeter across a 1-μF capacitor, your eye can resolve if the capacitor's value is 0.1 times or 10 times as large as it should be. You can't perform this kind of test with a DVM.

Another advantage of analog meters is that they are passive devices: They don't inject noise into your circuit as digital meters can.

6 A general-purpose function generator. In addition to supplying the drive signal for your circuit, you can use function generators to feed current via a resistor into a node while you check for the correct circuit response. While sine and square waves are popular test signals, I have often found triangular waveforms to be invaluable when searching for nonlinearities.

7 Power supplies with stable outputs. They should have coarse and fine adjustment controls and adjustable current limits. Digital controls are usually not suitable; they don't let you continuously sweep the voltage up and down while you monitor the scope and watch for trends. In cases when the power supply's output capacitor causes problems, you may want a power supply whose output circuit, like that of an op amp, includes no output capacitor. You can buy such a supply, or you can make it with an op amp and a few transistors. The advantage of the supply shown in **Fig 4** is that you can design it to slew fast when you want it to. Also, if a circuit latches and pulls its power supply down, the circuit won't destroy itself by discharging a big capacitor.

Along the lines of power, another useful troubleshooting tool is a set of batteries. You can use a stack of one, two, or four 9V batteries, gel cells, or whatever is convenient. Batteries are useful as an alternate power supply for low-noise preamplifiers. If the preamp's output doesn't get quieter when the batteries are substituted for the ordinary power supply, don't blame your circuit troubles on the power supply. You can also use these batteries to power low-noise circuits, such as those sealed in a metal box, without contaminating their signals with any external noise sources.

8 A few RC substitution boxes. You can purchase the VIZ Model WC-412A "twiddle-box" **(Fig 5)** from Fordham Radio (Hauppauge, NY). You can set the

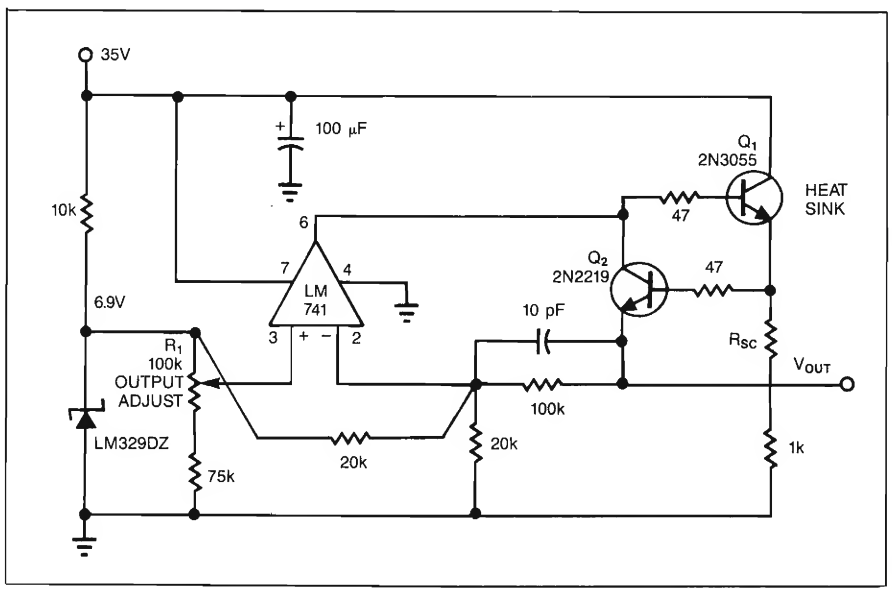



***Fig 4—You can vary the output voltage** of this dc power supply from 3 to 30V by adjusting $R_1$. $R_{SC}$ should be between 3 and 100Ω; the short-circuit current is equal to 600mV/ $R_{SC}$ + 20mA.*

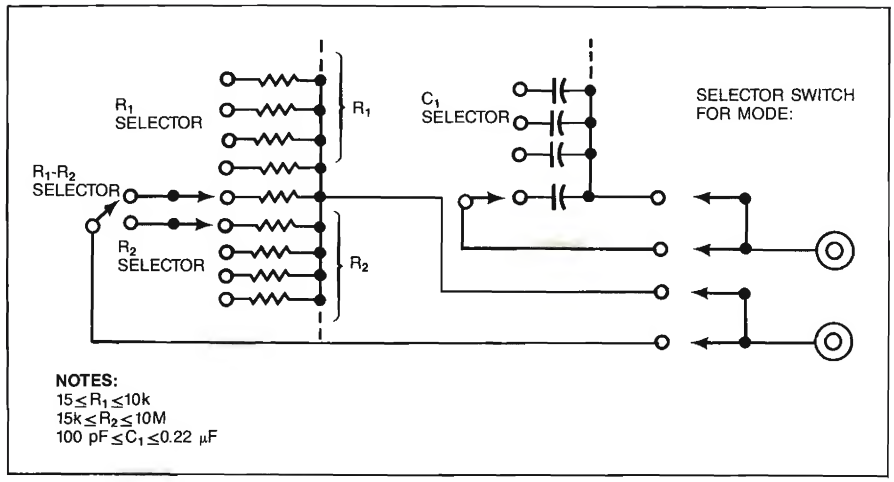



***Fig 5—This general schematic is for a commercially available R-C substitution box,*** *the VIZ Model WC-412A from Fordham Radio (Hauppauge, NY). The unit costs around $89 and has resistor and capacitor values in the range of 15Ω to 10 MΩ and 100 pF to 0.2 µF, respectively. It can be configured to be an open circuit, a series R-C, resistors, capacitors, a parallel R-C, or a short circuit.*

unit in the following modes: R, C, series R-C, parallel R-C, open circuit, or short circuit. They are invaluable for running various "tests" that can lead to the right answer.

You may need component values beyond what the twiddle boxes offer; in our labs, we built a couple of home-brew versions (**Fig 6**). The circuit shown in **Fig 6a** provides variable low values of capacitance and is useful for fooling around with the damping of op amps and other delicate circuits. You can make your own calibration labels to mark the setting of the capacitance and resistance values. The circuit shown in **Fig 6b** provides high capacitance for testing power supplies and damping various regulators.

**9** An isolation transformer. If you are working on a line-operated switching regulator, this transformer helps you avoid lethal and illegal voltages on your test setup and on the body of your scope. If you have trouble obtaining an isolation transformer, you can use a pair of transformers (step-down, step-up) back-to-back (**Fig 7**). Or, if cost isn't an issue, you can use isolated probes. These probes let you display small signals that have common-mode voltages of hundreds of volts with respect to ground, and they won't require you to wear insulated gloves when adjusting your scope.

**10** A variable autotransformer. This instrument lets you change the line voltage and watch its effect on the circuit. (Warning: A variable auto-transformer is NOT normally an isolation transformer.)

**11** A curve tracer. A curve-tracer can show you that two transistors may have the same saturation voltage under a given set of conditions even though the slope of one may be quite different from the slope of the other. If one of these transistors works well and the other badly, a curve tracer can help you understand why. A curve tracer can also be useful for spotting nonlinear resistances and conductances in diodes, capacitors, light bulbs, and resistors. It can test a battery by loading it down or recharging it and can check semiconductors for breakdown. And, when you buy the right adapters or cobble them up yourself, you can evaluate the shape of the gain, the CMRR, and the PSRR of op amps.

**12** Spare repair parts for the circuit-under-test. You should have these parts readily available, so you

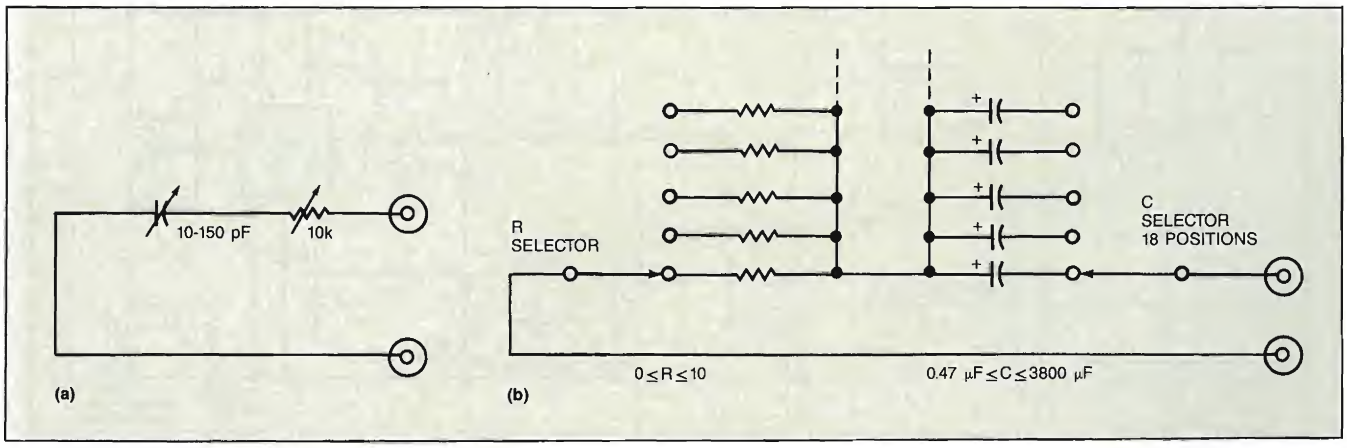
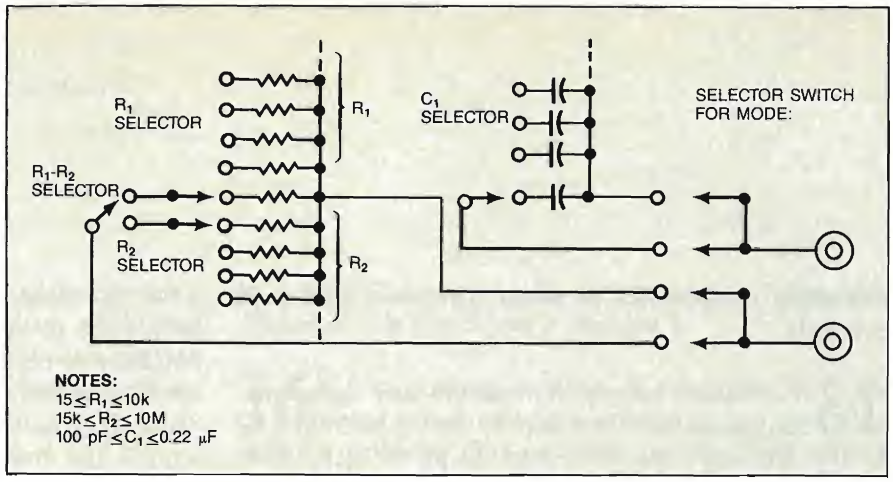



***Fig 6—R-C boxes based on these schematics extend component ranges*** *above those available in off-the-shelf versions. You can house the series R-C circuit in* ***a*** *in a 1×1×2-in. copper-clad box. Use the smaller plastic-film-dielectric tuning capacitors or whatever is convenient. Build the circuit in* ***b*** *with tantalum or electrolytic (for values of 1µF and higher) capacitors, but remember to be careful about their polarities and how you apply them. Also, you might consider using mylar capacitors for smaller valves. Use 18-position switches to select R and C values. And, stay away from wirewound resistors; their inductance is too high.*

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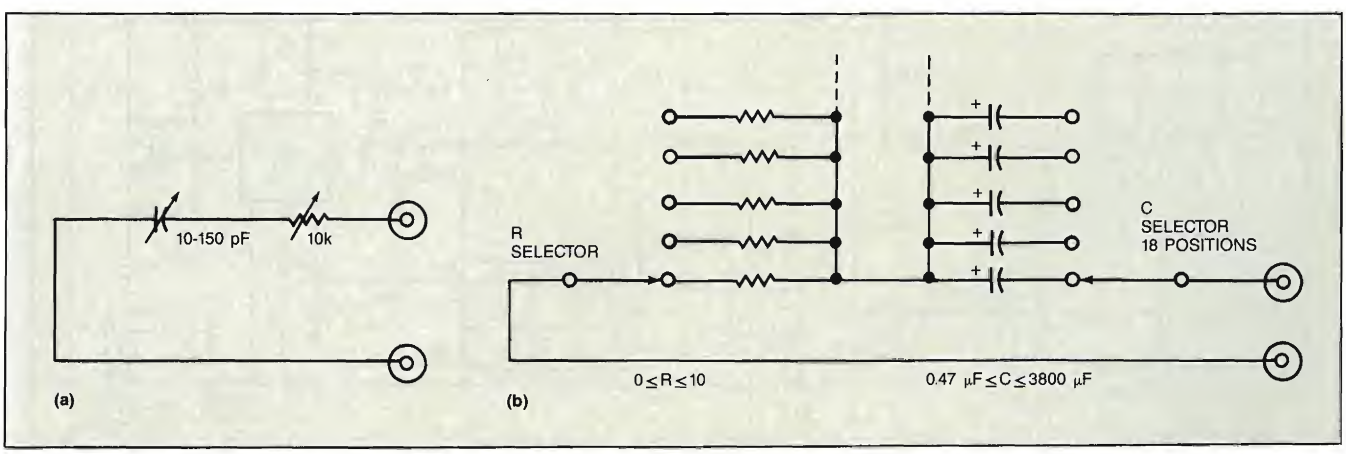


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*Be familiar with your equipment: Know how to use it and know its limitations.*

in handy. A few inches of this type of twisted-pair wire makes an excellent variable capacitor, sometimes called a "gimmick." Gimmicks are cheap and easy to vary by simply winding or unwinding them. Their capacitance is approximately 1 pF/in.

**14** Schematic diagrams. It's a good idea to have several copies of the schematic of the circuit-under-test. Mark up one copy with the normal voltages, currents, and waveforms to serve as a reference point. Use the others to record notes and waveform sketches that relate to the specific circuit-under-test. You'll also need a schematic of any homemade test circuit you plan to use. Sometimes, measurements made with your homemade test equipment may not agree with measurements made by purchased test equipment. The results from each tester may not really be "wrong;" they might differ because of some design feature, such as signal filtering. If you have all the schematics for your test equipment, you can more easily explain these incompatibilities. And, finally, the data sheets and schematics of any ICs used in the circuit will also come in handy.

**15** Access to any engineering or production test equipment, if possible. Use this equipment to be sure that when you fix one part of the circuit you aren't adversely affecting another part. Other pieces of equipment and testers also fall under the category of specialized test equipment; their usefulness will depend on your circuit. Two examples are a short-circuit-detector circuit (see **box,** "A short-circuit detector aids PCB repair") and a grid-dip meter (see **box,** "The grid-dip meter can direct you to trouble").

**16** A few working circuits, if available. By comparing a bad unit to a good one, you can often identify problems. You can also use the good circuits to make sure that your specialized test equipment is working properly.

**17** A sturdy, broad workbench. It should be equipped with a ground plane of metal that you can easily connect to the power ground. The purpose of this ground plane is to keep RF, 60-Hz, and all other noise from coupling into the circuit. Place insulating cardboard between the bench and the circuit-under-test, so that nothing tends to short to ground. Another way to prevent noise from interfering with the circuit is to use a broad sheet of single-sided copper-clad board. Placed copper-side down and with a ground wire soldered to the copper, it provides an alternate ground plane. To prevent electrostatic-discharge damage to CMOS circuits, you'll need a wrist strap to ground your body through 1 MΩ.

**18** Safety equipment. When working on medium- or high-power circuits that might explode with considerable power in the case of a fault condition, you should be wearing safety goggles or glasses with safety lenses. Keep a fire extinguisher nearby, too.

**19** A suitable hot soldering iron. If you have to solder or unsolder heavy buses from broad PCB

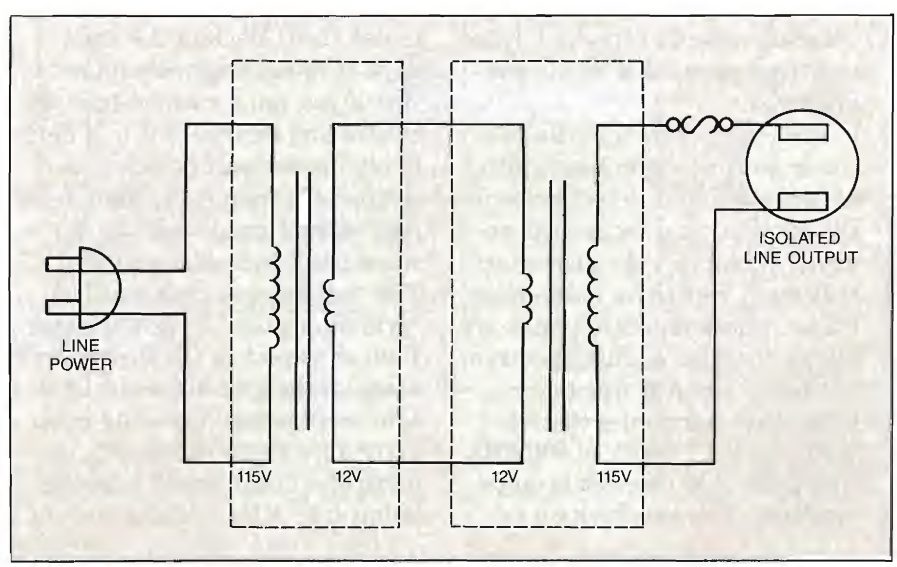


***Fig 7—You can use this back-to-back transformer configuration*** *to achieve line isolation similar to that of an isolation transformer.*

## The grid-dip meter can direct you to trouble

What do you do when trouble is everywhere? A typical scenario starts out like this: You make a minor improvement on a linear circuit, and when you fire it up you notice a terrible oscillation riding on the circuit's output. You check everything about the circuit, but the oscillation remains. In fact, the oscillation is riding on the output, the inputs, on several internal modes, and even on ground. You turn off the DVM, the function generator, the soldering iron, and the power supplies; but the oscillation is still there.

Now you start looking around the lab to see who has started a new oscillator or switching regulator that is doubling as a medium-power transmitter. Aside from yelling, "Who has a new circuit oscillating at 87 kHz?" what can you do to solve the problem? One useful tool is an ordinary AM transistor radio. As we have all learned, FM radios reject many kinds of noise, but AM radios scoop up noise at repetition rates and frequencies that would surprise you.

How can a crummy little receiver with an audio bandwidth of perhaps 5 kHz detect noise in the kilohertz and megahertz regions? Of course, the answer is that many repetitive noise-pulse trains, whose repetition rates are higher than the audible spectrum but below the AM frequency band, have harmonics that extend into the vicinity of 600 kHz, where the AM receiver is quite sensitive. This sensitivity extends to signals with amplitudes of just a few microvolts.

If you are skeptical about an AM radio's ability to detect these signals, tune the low end of an AM radio dial between stations. Then, place it near a DVM or a computer and listen for the hash. Notice, too, that the ferrite stick antenna has definite directional sensitivity, so you can estimate where the noise is coming from by using either the null mode or pointing the antenna to get the strongest signal. So, the humble AM radio may be able to help you as you hike around the lab and smile pleasantly at your comrades until you find the culprit whose new switching regulator isn't working quite right but which he neglected to turn off when he went out to get a cup of coffee.

On other occasions, the frequency and repetition rate of the noise are so high that an AM receiver won't be helpful in detecting the problem. What's the tool to use then? Back in the early days of radio, engineers found that if you ran a vacuum-tube oscillator and immersed it in a field of high-power oscillations at a comparable frequency, the tube's grid current would shift or dip when the frequencies matched. This tool became known as the "grid-dip meter." I can't say that I am an expert in the theory or usage of the grid-dip meter, but I do recall being impressed in the early days of monolithic ICs: A particular linear circuit was oscillating at 98 MHz, and the grid-dip meter could tickle the apparent rectified output error as I tuned the frequency dial back and forth.

That was 20 years ago, and, of course, Heathkit has discontinued their old Grid Dip and Tunnel Dip meters in favor of a more modern design. The new one, simply dubbed "Dip Meter," uses transistors and tetrode FETs. At the bargain price of $89, every lab should have one. They'll help you ferret out the source of nasty oscillations as high as 250 MHz. The literature that comes with the HD-1250 dip-meter kit also lists several troubleshooting tips.

When grid-dip meters first became popular, the fastest oscilloscope you could buy had a bandwidth of only a few dozen megahertz. These days, it is possible to buy a scope with a bandwidth of many hundreds of megahertz, so there are fewer occasions when you might need a grid-dip meter. Still, there are times when it is exactly the right tool. For example, you can use its oscillator to activate passive tuned circuits and detect their modes of resonance. Also, in a small company where you can't afford to shell out the many thousands of dollars for a fast scope, the Dip Meter is an inexpensive alternative.

*Don't forget about safety: Wear goggles when working on high-power circuits and keep a fire extinquisher near your workbench.*

(pc-board) traces, use a big enough iron or gun. For small and delicate traces around ICs, a small tip is essential. And, be sure that the iron is hot enough. An easy way to delaminate a trace or pad, whether you want to or not, is to heat it for too long a time. (The old Heathkit warnings not to use a hot iron became obsolete along with the germanium transistor.) In some cases, a grounded soldering iron is required; in others, a portable (ungrounded or rechargeable) soldering iron is ideal. Make sure you know whether your iron is grounded or floating.

**20** Tools for removing solder, such as solder wick or a solder sucker. You should be comfortable with whatever tools you are using; a well-practiced technique is sometimes critical for getting good results. If you are working on static-sensitive components, an antistatic solder sucker is less likely to generate high voltages due to internal friction than is a conventional solder sucker. I have been cautioned that a large solder sucker may cause problems when working on narrow PCB traces; in that case, solder wick may be the better choice.

**21** Hand tools. Among the tools you'll need are sharp diagonal nippers, suitable pliers, screwdrivers, large cutters, wrenches, wire-strippers, and a jack knife or Exacto knife.

**22** Signal leads, connectors, cables, BNC adapters, wires, clip leads, ball hooks, and alligator clips—as needed. Scrimping and chintzing in this area can waste lots of time: shaky leads can fall off or short out.

**23** Freeze mist and a hair dryer. The freeze mist available in aerosol cans lets you quickly cool individual components. A hair dryer lets you warm up a whole circuit. You'll want to know the dryer's output air temperature because that's the temperature to which you'll be heating the components.

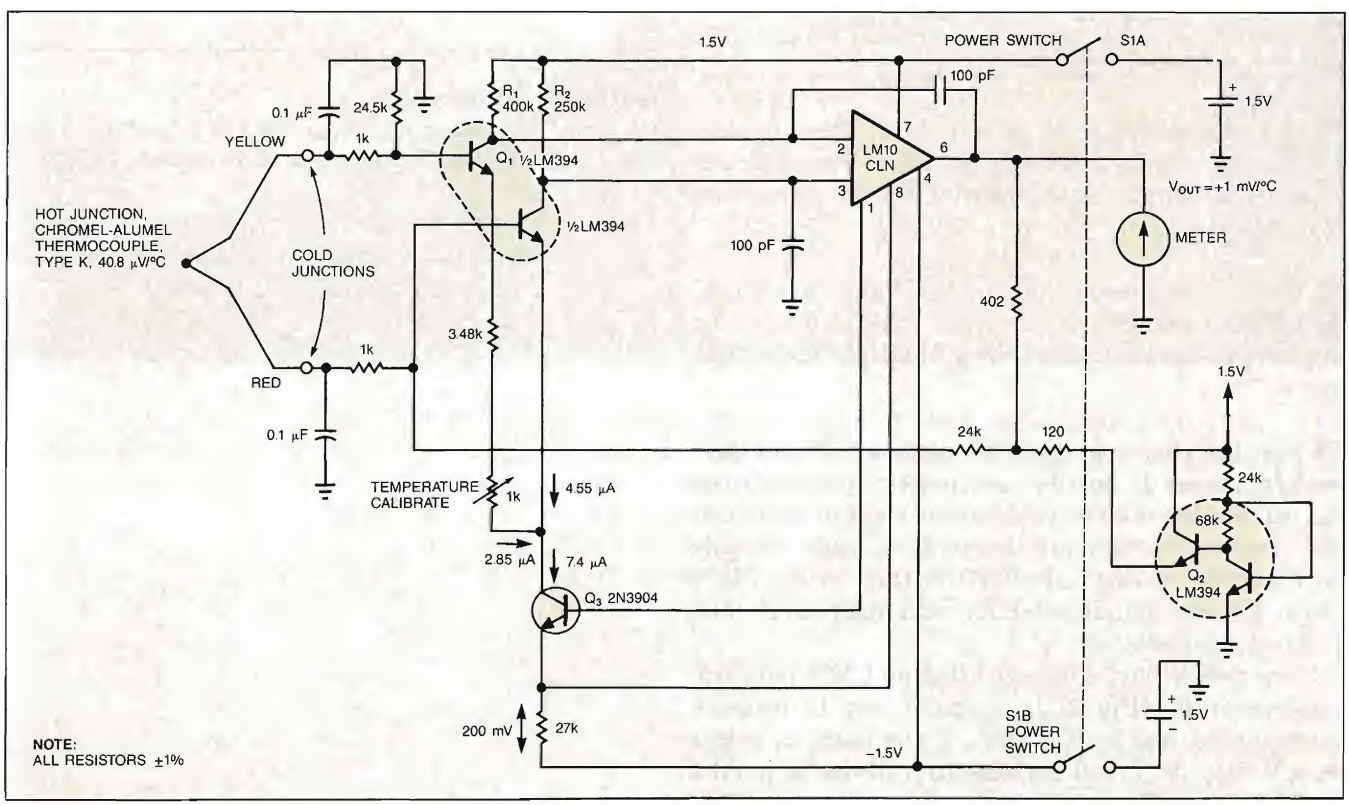


***Fig 8—This thermocouple amplifier*** *has inherent cold-junction compensation because of the two halves of $Q_1$, which run at a 1.6:1 current ratio. Their $V_{BE}$s are mismatched by 12 mV + 40.8 μV/°C. This mismatch exactly cancels out the 40.8 μV/°C of the cold junction. For best results, you should use four 100-kΩ resistors in series for $R_1$ and two 100-kΩ resistors in series with two 100-kΩ resistors in parallel for $R_2$. $Q_2$ and its surrounding components implement a correction for very cold temperatures and are not necessary for thermocouple temperatures above 0°C. (Credit goes to Mineo Yamatake for his elegant circuit design.)*

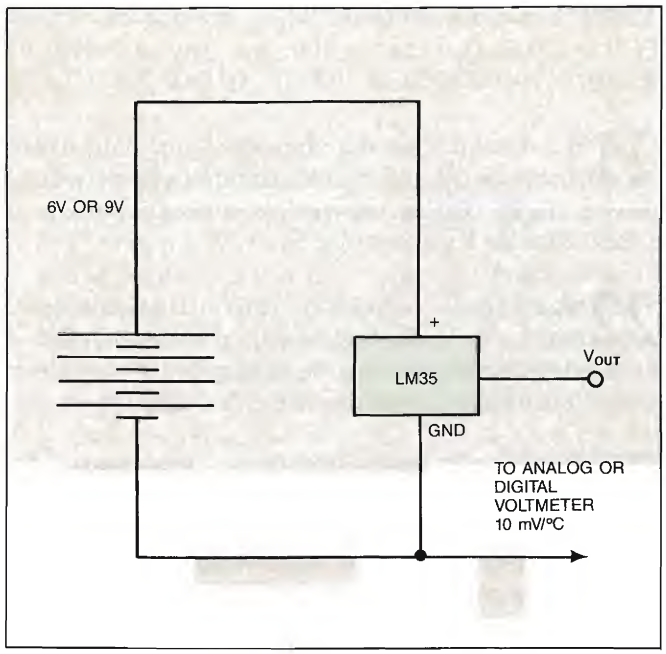


***Fig 9—Beware of using this circuit*** *to measure the temperature of very small objects; it will give you less accurate readings than a tiny thermocouple with small wires.*

**24** A magnifying glass or hand lens. These devices are useful for inspecting boards, wires, and components for cracks, flaws, hairline solder shorts, and cold-soldered joints.

**25** An incandescent lamp or flashlight. You should be able to clearly see what you are doing, and bright lights also help you to inspect boards and components.

**26** A thermocouple-type thermometer. If your thermometer is floating and battery powered, you can connect the thermocouple to any point in the circuit and measure the correct temperature with virtually no electrical or thermal effect on the circuit. **Fig 8** shows a thermocouple amplifier with designed-in cold-junction compensation.

Some people have suggested that an LM35 temperature-sensor IC (**Fig 9**) is a simple way to measure temperature, and so it is. But, if you touch or solder an LM35 in its TO-46 package to a device in a TO-5 or TO-3 case, the device's leads will increase the thermal mass and conduct heat away from the device whose temperature you are trying to measure. Thus, your measurements will be less accurate than if you had used a tiny thermocouple with small wires.

You've come to the end of my list of essential equipment for ordinary analog-circuit troubleshooting. Depending on your circuit, you may not need all these items; and, of course, the list did not include a multitude of other equipment that you may find useful. Logic analyzers, impedance analyzers, spectrum analyzers, programmable current pumps, capacitance meters and testers, and pulse generators can all ease various troubleshooting tasks.

Each of you will have your own idea of what is essential and what is unnecessary for your special case, and I would be delighted to get feedback on this subject. You can write to me at Mail Stop C2500A, National Semiconductor Corp, Box 58090, Santa Clara, CA 95052. EDN

## References

1. Collins, Jack, and David White, "Time-domain analysis of aliasing helps to alleviate DSO errors," *EDN*, September 15, 1988, pg 207.

## Author's biography

For information about Bob Pease, see the box, "Who is Bob Pease, anyway?" in the January 5, 1988, edition of EDN.

**Article Interest Quotient (Circle One)**
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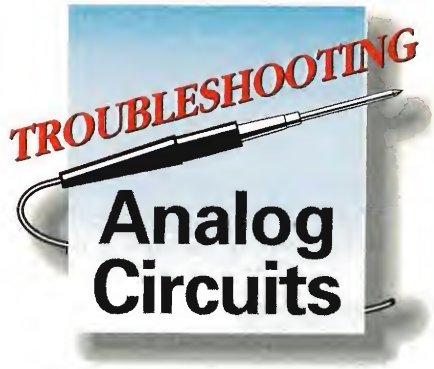



PART 3

# Troubleshooting gets down to the component level

*In recent issues, this series has covered the philosophy of troubleshooting analog circuits and the tools and equipment you need to do so. But if you're working on a circuit and are not aware of what can cause component failure, finding the root of your problem could be difficult. Hence, this installment covers resistors, inductors, and transformers; their possible modes of failure; and the unsuspected problems that may occur if you use the wrong type of component. Capacitors will be covered in the next installment.*

Robert A Pease, *National Semiconductor Corp*

Troubleshooting circuits often boils down to finding problems in passive components. These problems can range from improper component selection in the design phase to damaged components that hurt the circuit's performance. Resistors, inductors, and transformers can each be a source of trouble.

Resistors are certainly the most basic passive component, and, barring any extreme or obscure situations, you won't usually run into problems with the parts themselves. I don't mean to say that you'll never see any problems, but most of them will be due to the way you use and specify resistors. In other cases, some other part of the circuit may be causing damage to a resistor, and the failure of the resistor is just a symptom of a larger problem.

You may eventually have to track down a wide variety of problems involving resistors to achieve a working design. Some will seem obvious. For example, your circuit needs a 10-kΩ resistor. The technician reaches into the drawer for one and instead gets a 1-kΩ resistor, which then mistakenly gets inserted into your board. This example illustrates the most common source of resistor trouble in our lab. Consequently, I ask my technicians and assemblers to install resistors so that their values are easy to read.

Sometimes a resistor gets mismarked; sometimes a resistor's value shifts due to aging, overheating, or temperature cycling. Recently, we found a batch of metal-film resistors whose values had increased by 20 to 900% after just a few dozen cycles of −55 to +125°C. As it turned out, our QC department had okayed only certain resistors to be used in burn-in boards, and these particular resistors had not been okayed.

### Resistor characteristics can vary widely

You should be familiar with the different resistor types in order to select the most appropriate type for your application; the most common types and some of their characteristics are summarized in **Table 1.** A component type that's good for one application can be disas-

*Transformer problems can be due to an incorrect turns ratio or an incorrect winding polarity.*

## TABLE 1—TYPICAL RESISTOR CHARACTERISTICS

| RESISTOR TYPE | RANGE* (Ω) | TC (±PPM/°C) | PARASITIC EFFECTS | COST |
|---|---|---|---|---|
| COMPOSITION | 1–22M | HIGH | LOW | LOW |
| METAL FILM | 10–1M | LOW | MEDIUM | MEDIUM |
| CARBON FILM | 10–10M | MEDIUM | MEDIUM | MEDIUM |
| WIREWOUND | 1–273k | LOW | HIGH | HIGH |
| THIN-FILM | 25–100k | LOW | LOW | MEDIUM |
| THICK-FILM | 10–1M | LOW | LOW | MEDIUM |
| DIFFUSED | 20–50k | HIGH | HIGH | LOW |

*RANGE MAY VARY BY MANUFACTURER.

trous in another. For example, I often see an engineer specify a carbon-composition resistor in a case where stability and low TC are required. Sometimes it was just a bad choice, and a conversion to a stable metal-film resistor with a TC of 100 ppm/°C max considerably improves accuracy and stability. In other cases, the engineer says, "No, I tried a metal-film resistor there, but, when I put in the carbon resistor, the overall TC was improved." In this case, the engineer was relying on the carbon-composition resistor to have a consistent TC. I have found that you can't rely on consistent TC with the carbon-composition type, and I do not recommend them in applications where precision and stability are required.

However, carbon-composition resistors do have their place. I was recently reviewing a military specification that spelled out the necessary equipment for the ESD testing of circuits. An accurate 1500Ω resistor was required for use as the series resistor during discharge of the high-voltage capacitor. In this case, you would assume that a metal-film resistor would be suitable; however, a metal-film resistor is made by cutting a spiral into the film on the resistor's ceramic core (**Fig 1a**). Under severe overvoltage conditions, the spiral gaps can break down and cause the resistor to pass a lot more current than Ohm's Law predicts—the resistor will start to destroy itself. Therefore, the spec should have called for the use of a carbon-composition resistor, whose resistive element is a large chunk of resistive material (**Fig 1b**). This resistor can handle large overloads for a short time without any such flashover. Even when you are applying a 200 to 400%

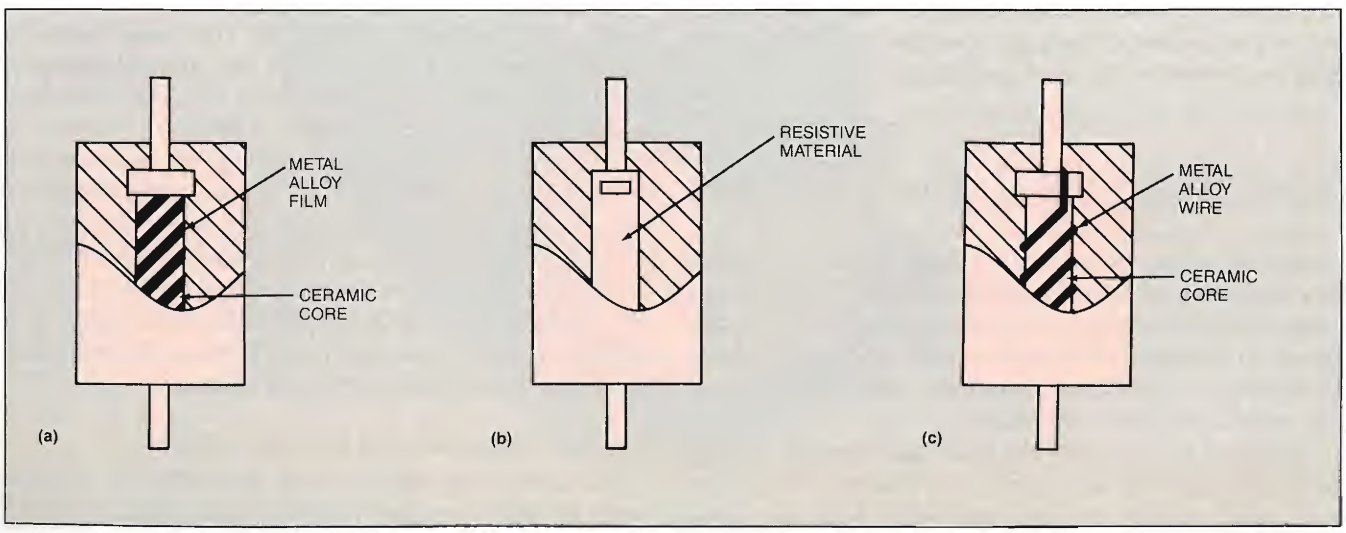



***Fig 1—Film resistors (a) are made by cutting a spiral into a layer of metal or carbon*** *deposited on a nonconductive core. Carbon composition types* ***(b)*** *have a solid core of resistive material; wirewound resistors are formed by winding resistive wire on a nonconductive core* ***(c)****.*

overload for just a short time, the nonuniform heating of the spiralled section of a metal-film resistor can cause the resistor to become unreliable. You can get around this problem by using a series connection of metal-film resistors. If you put fifteen 100Ω, ¼W metal-film resistors in series, an individual resistor would not see overvoltage or excessive power.

Carbon-film resistors are now quite inexpensive and have become the most common type of resistor around most labs. Their main drawback is that they are very similar in appearance to metal-film resistors and have some similar characteristics: Carbon-film resistors have 1% tolerances, are normally manufactured with spiral cuts, and have the same kind of voltage-overload limitations as metal-film types. But, carbon-film resistors have much higher TCs—500 to 800 ppm/°C. It's easy to mistakenly substitute a drifty carbon-film resistor for the intended metal-film type. Don't confuse the two.

Precision-film resistors, on the other hand, are available with greatly improved accuracy and TC. Compared to ordinary RN55D and RN55C resistors with TCs of 100 or 50 ppm/°C, these resistors have TCs as good as 20, 10, 5 or 2 ppm/°C and accuracies as good as 0.01%. These resistors are comparable to small precision wirewound resistors but are generally smaller and less expensive. They also have less inductance than the wirewound types and, thus, are suitable for higher-speed operation. A few spirals on a film substrate add negligible inductance compared to the hundreds or thousands of turns on a wirewound resistor's bobbin. Precision-film resistors are also available in matched sets of discrete resistors whose relative accuracy and TC tracking are better than those of individual resistors.

You can also buy custom thin-film resistor networks on a single substrate if your requirements are critical. A more economical route is to use four, seven, or eight matched precision thin-film resistors in a DIP. I have found the TC tracking of these devices from several manufacturers to be better than 1 ppm/°C. These sets are ideal for precision amplifier stages and DACs. Also, when you buy resistors, leave them on the tape. When you need matched sets, you can pull off adjacent resistors and be reasonably confident that they will match and track well.

Traditionally, the best, most stable resistors have been wirewound resistors (**Fig 1c**). These days, film resistors can match wirewound resistors quite well for almost any set of specifications. However, for a resistor whose value is between 200 kΩ and 1 MΩ, wirewound

***Bob uses carefully selected precision resistors*** *to model the resistance of the metal runs of a FET op amp.*

resistors are more expensive and come only in larger packages. Wirewound resistors also have one major disadvantage: the inductance of an ordinary wirewound resistor makes achieving fast (sub-μsec) settling impossible. However, you can specify a special winding pattern that can greatly cut down the inductance of the windings. This type is listed in several manufacturers' catalogs as "Type HS." But I've found that there are two different types of HS: one type has almost zero inductance and greatly increased interwinding capacitance; the other type has low inductance and low capacitance and is well suited for fast-settling amplifiers. Be cautious of manufacturers' oversimplified statements.

A tricky problem popped up a couple of years ago when we assembled a precision amplifier with wirewound resistors. The output was drifting all over the place, but the amplifier, zeners, and transistors were stable. What was drifting? It turned out that a wirewound resistor was "drifting" because we had mistakenly used a special temperature-compensating resistor with a TC of +3300 ppm/°C. This type of temperature-compensating resistor is often used for correcting the TC of transistor logging circuits, but it wasn't labelled in an obvious way. When we put this resistor in a circuit where a low-TC resistor was required, it took us a couple of hours of troubleshooting to pinpoint the problem.

### Match the TC to the application

Diffused resistors, commonly used in ICs, have some strange characteristics. Their TC is high—+1600 ppm/°C—and includes a nonlinear, or quadratic, term. Thus,

*Resistor problems are often due to using the wrong type of resistor for your application.*

the resistance goes up faster at high temperatures than it falls at cold temperatures. These resistors would be useless except for one minor detail: They track at the rate of approximately ±5 ppm/°C. Since it is very inexpensive to make matched pairs or sets of these resistors in a monolithic integrated circuit, their use is popular among IC designers. If you're not designing an IC, though, you probably won't meet up with diffused resistors very often.

Many ICs, such as DACs and voltage references, are made with thin-film (sichrome or nichrome) resistors on the chip. Compared with most other resistor types, these resistors have the somewhat lower TCs of 50 to 350 ppm/°C, closer ratios, better long-term stability, better TC tracking, and less nonlinearity of the "voltage coefficient." This last term refers to the nonlinearities in Ohm's Law that occur when there is a large voltage drop across a resistor; the effect is most common in resistors with large values.

Therefore, when you drive the reference input to a DAC, you should be aware that the $R_{in}$ will only shift 1 to 3% over the entire temperature range. However, there may still be a broad tolerance, as it is not easy to keep tight tolerances on the "sheet rho," or resistivity, during the IC's production. For example, a typical DACs $R_{in}$ specification is 15 kΩ ± 33%. These film resistors have even better tracking TC than diffused resistors, often better than 1 ppm/°C.

In addition to the TC, you might also be concerned with the shunt capacitance of a resistor. Recently, I was trying to build a high-impedance probe with low shunt capacitance. I wanted to put a number of 2.5-MΩ resistors in series to make 10 MΩ. I measured the shunt capacitance of several resistors with our lab's impedance bridge. A single Allen-Bradley carbon-composition resistor had a 0.3-pF capacitance, so the effective capacitance of four in series would be down near 0.08 pF—not bad (**Fig 2**). Then I measured a Beyschlag carbon-film resistor. Its capacitance was slightly lower, 0.26 pF. The capacitance of a Dale RN60D was 0.08 pF; the capacitance of four in series would be almost unmeasurable.

It would be an improper generalization to state that certain resistor types have less shunt capacitance than others. However, the main point is that if you need a resistance with low shunt capacitance, you can connect lower-value resistors in series.

As with the fixed resistors discussed so far, there are many kinds and types of variable resistors, such as trimming potentiometers, potentiometers, and rheo-

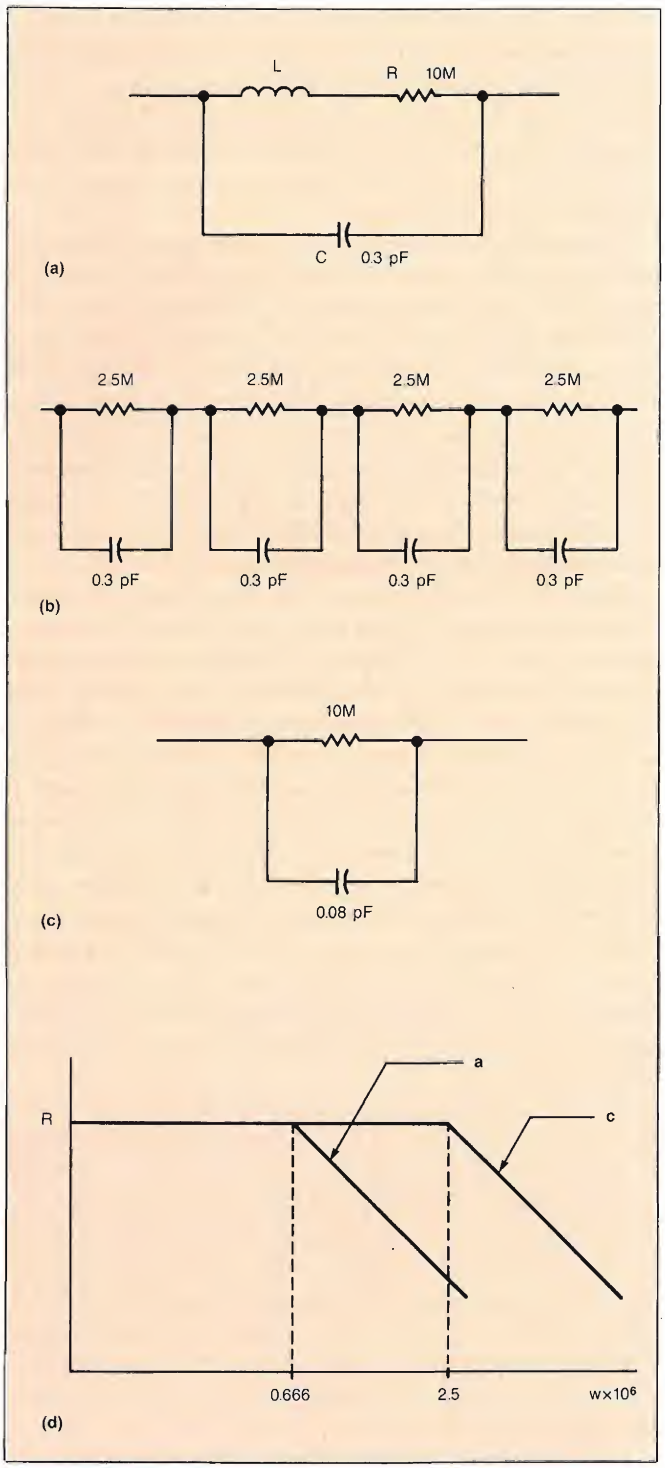



***Fig 2—You can reduce the capacitance** of a single resistor **(a)** by using several resistors in series as shown in **b** (assume the inductance is negligible). This series resistor configuration has one fourth of the single resistor's capacitance **(c)** and extends the resistor's frequency response as shown in **d**.*

stats. These resistors are made with many different resistive elements, such as carbon, cermet, conductive plastic, and wire. As with fixed resistors, be careful of inexpensive carbon resistors, which may have such poor TC that the manufacturer avoids any mention of it on the data sheet. These carbon resistors would have a poor TC when used as a rheostat but might have a good TC when used as a variable voltage divider or a potentiometer. On the other hand, some of the cermet resistors have many excellent characteristics but are not recommended for applications that involve many hundreds of wiper cycles. For example, a cermet resistor would be inappropriate for a volume control on a radio.

The major problem area for variable resistors is their resolution, or "settability." Some variable resistors claim to have infinite resolution; but, if you apply 2V across a variable resistor's ends and try to trim the wiper voltage to any or every millivolt in between, you may find that there are some voltage levels you can't achieve. So much for infinite resolution. As a rule of thumb, a good pot can usually be set to a resolution of 0.1%, or every 2 mV in the previous case. Thus, counting on a settability of 0.2% is conservative.

Good settability includes not only being able to set the wiper to any desired position but also having it stay there. But, I still see people advertising multiturn pots with the claimed advantage of superior settability. The next time you need a pot with superior settability, evaluate a multiturn pot and a single-turn pot. Set each one to the desired value, tap the pots with a pencil, and tell me which one stays put. I normally expect a multiturn pot, whether it has a linear or circular layout, to be a factor of 2 to 4 worse than a single-turn pot because the mechanical layout of a single-turn pot is more stable and balanced. Does anyone know of an example in which the multiturn pot is better?

**Don't exceed your pot's I and V ratings**

How do variable resistors fail? If you put a constant voltage between the wiper and one end and turn the resistance way down, you will exceed the maximum wiper current rating and soon damage or destroy the wiper contact. Note that the power rating of most variable resistors is based on the assumption that the power dissipation is uniformly distributed over the entire element. If half of the element is required to dissipate the device's rated power, the pot may last for a short while. However, if a quarter of the element is required to dissipate this same amount of power, the pot will fail quickly. For example, many years ago, the only ohmmeters available might put as much as 50 mA into a 1-Ω resistor. When a 50-kΩ, 10-turn precision potentiometer (think of a $20 item) was tested at

## Consider the effects of magnetic fields

One problem recently illustrated the foibles of inductor design: Our applications engineers had designed several dc/dc converters to run off 5V and to put out various voltages, such as +15V and −15V dc. One engineer built his converter using the least expensive components, including a 16-cent, 300-μH inductor wound on a ferrite rod. Another engineer built the same basic circuit but used a toroidal inductor that cost almost a dollar. Each engineer did a full evaluation of his converter; both designs worked well.

Then the engineers swapped breadboards with each other. The data on the toroid-equipped converter was quite repeatable. But, they couldn't obtain repeatable measurements on the cheaper version. After several hours of poking and fiddling, the engineers realized that the rod-shaped inductor radiated so much flux into the adjacent area that all measurements of ac voltage and current were affected. With the toroid, the flux was nicely contained inside the core, and there were no problems making measurements. The engineers concluded that they could build the cheapest possible converter, but any nearby circuit would be subject to such large magnetic fields that the converter might be useless.

When I am building a complicated precision test box, I don't even try to build the power supply in the main box because I know that the magnetic fields from the power transformer will preclude low-noise measurements and the heat from the transformer and regulators will degrade the instrument's accuracy. Instead, I build a separate power-supply box on the end of a 3-ft cable; the heat and magnetic flux are properly banished from my precision circuits.

*The easiest way to spot problems with resistors and inductors is to follow your nose.*

incoming inspection using such an ohmmeter, the tester would turn the pot down to the end where the 50 mA was sufficient to burn out the delicate wirewound element—an inefficient way to test parts.

Some trimming potentiometers are not rated to carry any significant dc current through the wiper. This dc current—even a microampere—could cause electromigration, leading to an open circuit or noisy, unreliable wiper action. Carbon pots are not likely to be degraded by this failure mode. If you have any questions about the suitability of your favorite trimming potentiometers for rheostat service, you or your components engineer should ask the pot's manufacturer.

How do you spot resistor problems? The most obvious way is to follow your nose. When a resistor is dying it gets quite hot, and sometimes the strong smell leads right to the abused component. Just be careful not to burn your fingers.

You may also encounter situations in which a resistor hasn't truly failed but doesn't seem to be doing its job, either. Something seems to be wrong with the circuit, and a resistor of the wrong value is the easiest explanation. So, you measure the resistor in question, and 90% of the time the resistor is just fine—usually the trouble is elsewhere. A resistor doesn't usually fail all by itself. Its failure is often a symptom that a transistor or circuit has failed; if you just replace the resistor, the new one will also burn out or exhibit the same strange characteristics.

How do you check for resistor errors? If you're desperate, you can disconnect one end of the resistor and actually measure its value. It's often easier to just measure the $I \times R$ drops in the network and deduce which resistor, if any, seems to be of the wrong value. If one resistor is suspected of being temperature sensitive, you can heat it with a soldering iron or cool it with freeze mist as you monitor its effect. In some solid-state circuits, the signals are currents, so it's not easy to probe the circuit with a voltmeter. In this case, you may have to make implicit measurements to decide if a resistor is the problem. Also, remember that a sneak path of current can often cause the same effect as a bad resistor.

### Watch out for damaged components

Damaged resistors can also be the source of trouble. A resistor that's cracked can be noisy or intermittent. When resistors are overheated with excess power, such as 2 or 3W in a ¼W resistor, they tend to fail "open"—they may crack apart, but they don't go to low ohms or to a short circuit. The accuracy or stability of a high-value resistor ($10^8$ to $10^{12}\Omega$) can be badly degraded if dirt or fingerprints touch its body. Careful handling and cleaning are important for these high-value resistors and high-impedance circuits.

One problem that occurs with all resistors is related to the Seebeck effect: the production of an EMF in a circuit composed of two dissimilar metals when their two junctions are at different temperatures. In precision circuits, you should avoid thermal gradients that could cause a large temperature difference across a critical resistor. Many precision wirewound and film resistors have low Seebeck coefficients in the range 0.3 to 1.5 $\mu V/°C$. But avoid tin oxide resistors, which have a thermocouple effect as large as 100 $\mu V/°C$. If you are going to specifiy a resistor for a critical application where thermocouple errors could degrade circuit performance, check with the manufacturer.

So, know that resistors can present challenging troubleshooting problems. Rather than reinventing the wheel every time, try to learn from people with experience.

### Inductors and transformers aren't so simple

Inductors and transformers are more complicated than resistors—nonlinearity is rife. Their cores come in many different shapes and sizes, from toroids to pot cores and from rods to stacks of laminations. Core materials range from air to iron to any of the ferrites. I am not going to presume to tell you how to design an inductor or transformer or how to design circuits that use them, but I will discuss the kinds of trouble you can have with these components. For example, you can have a good core material; but, if there is an air gap in the core and you don't carefully control the gap's width, the energy storage and the inductance of the component can vary wildly. If someone has substituted a core of the wrong material, you may have trouble spotting the change; an inductance meter or an impedance bridge can help. But even with one of those tools, you're not home free.

For most inductors and transformers with cores composed of ferromagnetic materials, you had better make sure that the test conditions—the ac voltage and the frequency that the measuring instrument applies to the device under test—closely approximate those the component will see in your real-life application. If you fail to take such precautions, your inductance measurements stand a good chance of seriously misleading you and making your troubleshooting task much more frus-

trating. The phenomena you are likely to run into as a result of incorrect test conditions include saturation, which can make the inductance look too low, and core loss, which can lower the Q of an inductor. For transformers, make sure you understand which of the inductances in the device's equivalent circuit you are measuring. (For more on transformer equivalent circuits see **box**, "Equivalent circuits demystify transformers.")

When you work with inductors or transformers, you have to think in terms of current: In any transformer or inductor, flux is directly proportional to the current, and resistive losses are directly proportional to the current squared. Therefore, be sure to have several current probes, so you can observe what the current waveforms are doing. After all, some of the weirdest, ugliest, and most nonideal waveforms you'll see are the waveforms associated with inductors.

In the absence of an instrument designed to measure inductance, parallel the inductor with a known capacitance to create a parallel resonant circuit. If you use a high-impedance source to apply a current pulse to this circuit, you can determine the inductor's value from the resonant frequency and the capacitance: $f = 1/2\pi \cdot \sqrt{LC}$. If you look at the inductor's waveform on a scope, you can compare it to the waveform you get with a known-good inductor. This technique is also good for spotting a shorted turn, which reduces inductance nearly to zero. The L meter and the similar Q meter can help you ensure that good inductors haven't been

## Equivalent circuits demystify transformers

You can represent a transformer with a turns ratio of N as a "T" network (**Fig A**). N equals $N_1/N_2$, where $N_2$ is the number of secondary turns and $N_1$ is the number of primary turns. However, if you plan to make measurements on transformers, it's helpful to keep the equivalent circuit shown in **Fig B** in mind. For example, the inductance you measure between terminals A and B is quite large if you leave terminals C and D open, but the measured inductance is quite small if you short terminals C and D together.

In the first case, you are measuring the mutual inductance plus the leakage inductance of the primary. But because the leakage inductance is normally much, much smaller than the mutual inductance, you are measuring the leakage inductance of the primary plus the reflected secondary leakage in the second case.

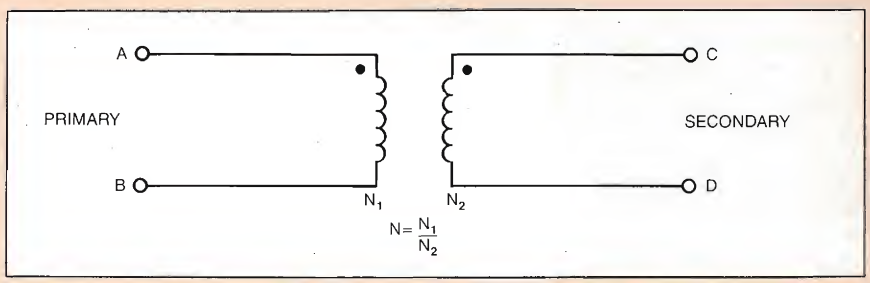



***Fig A—In most instances,*** *you can represent a transformer by its turns ratio.*

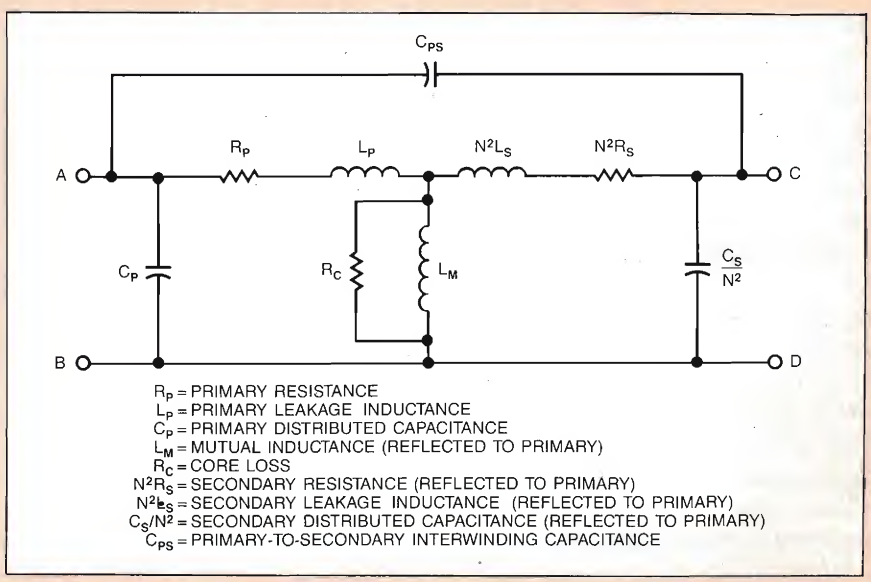



***Fig B—If you are measuring the characteristics of transformers,*** *you should keep its equivalent circuit in mind. Considering the effect of each component will help you understand the results of your measurements.*

*When working with inductors or transformers, think in terms of current and use current probes to view the waveforms.*

damaged by saturation.

Incredible as it may sound, you can permanently damage an inductor by saturating it. Some ferrite toroids achieve their particular magnetic properties by dint of operation at a particular point on the material's magnetization curve. Saturating the core can move the operating point and drastically change the core's magnetic properties. The likelihood of your being able to return the material to its original operating point is small to nonexistent. In other cases, as a result of applying excessive current, the core temperature increases to a point where the core's magnetic properties change irreversibly. Regardless of the mechanism that caused the damage, you may have to do as I once did—package the inductors with a strongly worded tag to demand that nobody test them at Incoming Inspection.

If you choose too small a wire size for your windings, the wire losses will be excessive. You can measure the winding resistance with an ohmmeter, or you can measure the wire's thickness. But if the number of turns is wrong, you can best spot the error with an L meter—remember that $L \propto N^2$. Be careful when using an ohmmeter to make measurements on transformers and inductors—some ohmmeters put out so many milliamps that they are likely to saturate the component you are trying to measure and at least temporarily alter its characteristics.

**Protect transistors from voltage kick**

There is one trouble you can have with an inductor that will not do any harm to the magnetic device but will leave a trail of death and destruction among its associated components: When you use a transistor to draw a lot of current through an inductor and then turn the transistor off, the "kick" from the inductor can generate a voltage high enough to destroy almost any transistor. You can avoid this problem by connecting a suitable snubber, such as a diode, an RC network, a zener, or a combination of these components, across the inductor to soak up the energy. The use of a snubber is an obvious precaution, yet every year I see a relay driver with no clamp to protect the transistor. The transistor may survive for a while, but not for long.

The tiniest inductors are called beads. They are about the same size and shape as beads worn as jewelry and have room for only one or two or four turns of wire. Beads are commonly used in the base or emitter of a fast transistor to help keep it from oscillating. A bead not only acts inductive but also acts lossy at high frequencies, thus damping out ringing. In general, the choice of a bead is an empirical, seat-of-the-pants decision, but designers who have a lot of experience in this area make good guesses. This topic is one that I have not seen treated, except perhaps one sentence at a time, in any book or magazine. You'll just have to get a box of ferrite beads and experiment.

Transformers usually are susceptible to the same problems as inductors. In addition, the turns ratio may be wrong, or the winding polarity might be incorrect. And, if your wire-handling skills are sloppy, you might have poor isolation from one winding to another. Most ferrite materials are insulators, but some are conductive. So, if you've designed a toroidal transformer whose primary and secondary windings are on opposite sides of the toroid and you scrape off the core's insulating coating, you could lose your primary-secondary insulation. If the insulating coating isn't good enough, you might want to put tape over the toroid.

Fortunately, it's easy to establish comparisons between a known-good transformer and a questionable one. If you apply the same input to the primaries of both transformers, you can easily tell if the secondaries are matched, wound incorrectly, or connected backwards. If you're nervous about applying full line voltage to measure the voltages on a transformer, don't worry—you can drive the primary with a few volts of signal from a function generator and still see what the various windings are doing.

Two general problems can afflict power transformers. The first occurs when you have large filter capacitors and a big high-efficiency power transformer. When you turn the line power switch on, the inrush current occasionally blows the fuse. You might install a larger value of fuse, but then you must check to make sure that the fuse is not too high to offer protection. As an alternative, you could specify the transformer to have a little more impedance in the secondary: Use smaller wire for the windings or put a small resistor in series with the secondary.

Another approach, often used in TV sets, is to install a small negative-TC thermistor in the line power's path. The thermistor starts out with a nominal impedance, so the surge currents are finite. But then the thermistor quickly heats up, and its resistance drops to a negligible value. Thus, the efficiency of the circuit is quite good after a brief interval. If the circuit is a switch-mode power supply, the control IC should start up in a "soft-start" mode. In this mode, the IC won't draw any extreme currents in an attempt to charge

*In the absence of an instrument designed to measure inductance, parallel the inductor with a known capacitance to create a parallel resonant circuit.*

up the output capacitors too quickly. However, you must use caution when you apply thermistors for inrush current limiting: Beware of removing the input power and then reapplying it before the thermistors have had a chance to cool. A warm thermistor has low resistance and will fail to limit the current; thus, you are again likely to blow a fuse.

The second general problem with a line transformer occurs when you have a small output filter capacitor. In our old LM317 and LM350 data sheets, we used to show typical applications for battery chargers with just a 10-μF filter. Our premise was that when the transformer's secondary voltage dropped every 8 msec, there was no harm in letting the regulator saturate. That premise was correct, but we began to see occasional failed regulators that blew up when we turned the power on.

After extensive investigations, we found the problem in the transformer: If the line power switch was turned off at exactly the wrong time of the cycle, the flux in the transformer's steel core could be stored at a high level. Then, if the line power switch was reconnected at exactly the wrong time in the cycle, the flux in the transformer would continue to build up until the transfomer saturated and produced a voltage spike of 70 to 90V on its secondary. This spike was enough to damage and destroy the regulator. The solution was to install a filter capacitor of at least 1000 μF, instead of just 10 μF. This change cut the failure rate from about 0.25% to near zero.

Another problem occurred when the LM317 was used as a battery charger. When the charger output was shorted to ground, the LM317 started drawing a lot of current. But, the transformer's inductance kept supplying more and more current until the LM317 went into current limit and could not draw any more current. At this point, the transformer's secondary voltage popped up to a very high voltage and destroyed the LM317. The addition of the 1000-μF snubber also solved this problem.

### Inductors, like resistors, can overheat

How do you spot a bad inductor or transformer? I have already discussed several mechanisms that can cause the inductance or Q of an inductor to be inferior to that of a normal part. And, as with a resistor, you can smell an inductor that is severely overheating. Overheating can be caused by a faulty core, a shorted turn, incorrect wire gauge, or anything else that causes losses to increase. An open winding is easy to spot with an ohmmeter, as is a short from a primary to a secondary. If the pattern of winding has been changed from one transformer to another, you may not see it unless you test the components in a circuit that approximates the actual application. However, you may also be able to see such a discrepancy if you apply a fast pulse to the two transformers.

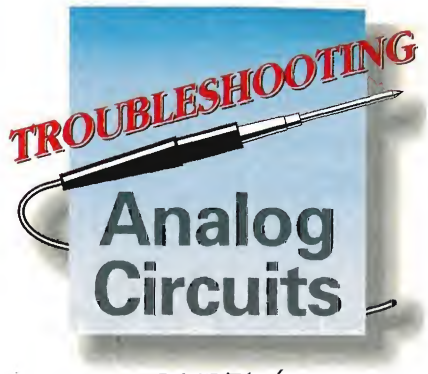
Tightly coupled windings, both bifilar and twisted pairs, have much better magnetic coupling and less leakage inductance than do well-separated primary and secondary windings. As the magnetic coupling improves, the capacitance between windings increases—but high capacitance between windings is often an undesirable effect in a transformer. An experienced transformer designer weighs all the tradeoffs and knows many design tricks—for example, the use of special pi windings and Litz wire. Mostly, you should know that these special techniques are powerful; if you ask the transformer designers the right questions, they can do amazing tricks.

I recently read about an engineer who designed an elegant shield made of mu-metal. However, the shield was difficult to install, so the technician had to tap on it with a hammer. When the engineer operated the circuit, the shielding seemed nonexistent—as if the shield were made of cardboard. After a lot of studying, the engineer realized that the mu-metal—which costs about $2 per 15 square inches, the same as a $2 bill—had been turned into perfectly worthless material by the pounding and hammering. In retrospect, the engineer had to admit that the mu-metal, when purchased, was prominently labelled with a caution against folding, bending, or hammering. So remember, in any area of electronics, there are problems with inductors and magnetic materials that can give you gray hair. EDN

## Author's biography

*For information about Bob Pease, see the box, "Who is Bob Pease, anyway?" in the January 5, 1988, edition of EDN.*

Article Interest Quotient (Circle One)
High 485 Medium 486 Low 487




**PART 4**

# A knowledge of capacitor subtleties helps solve capacitor-based troubles

*Earlier installments of this series have described a good analog troubleshooter's mindset, armamentarium of test equipment, and requisite knowledge of resistors, inductors, and transformers. Now, ace troubleshooter Pease reveals some of the secrets of an often-underestimated class of components—capacitors. And much of what you need to know to troubleshoot capacitor-related problems is not in any book—it's not even in data sheets.*

Robert A Pease, *National Semiconductor Corp*

Capacitors are rather remarkable. We consider capacitors, like resistors, to be "passive." But if you charge up a good as capacitor to 10V and take a 2-week vacation, when you come back the voltage may not have decreased by as much as 20 or even 10%. The capacitor may have stored and retained enough energy to run a micropower circuit for hours or to light an LED for a shorter interval. Calling components with such exceptional properties "passive" is more than a little unfair.

Ordinary, aluminum, electrolytic capacitors are most often used for power-supply filtering and bypassing. In the old vacuum-tube days, electrolytic capacitors were often used at levels of 150, 300, 500V, or more. There are several basic problems with these old circuits. First, if the voltage across a capacitor is much higher than 350V, the part's reliability is not nearly as good as that of devices operated below 350V. Also, if a piece of old equipment has not been powered up for years, it is advisable to apply the ac power gradually by cranking up the line voltage slowly with a variable transformer so that the electrolytic film has a chance to "form" up. If you hit it with full voltage instantly, an old capacitor may fail. Of course, if you are hit by high voltage, you may fail, too.

At this point, I should remind you that when working on high-voltage circuits, probe with one hand only and keep the other hand in your pocket. Avoid grounding your body at any other place and stand or sit on an insulating slab of dry material. These precautions can prevent a shock from causing you serious harm. When I start work on a high-voltage circuit, I solder a neon lamp in series with a 100-kΩ resistor across the high-voltage power supply as a glowing reminder that this circuit is powered by a voltage much higher than 15V.

After you operate a high-voltage power supply at full voltage, if you turn off the power and decide that for safety's sake you should short out the filters with a few hundred ohms, be careful. A few minutes later, the voltage on the capacitors may come back up to 60 or 80V and give you a shocking experience. The partial

*The partial recovery of voltage on a discharged capacitor is caused by "soakage," which causes the dielectric to "remember" the voltage it was recently biased at.*

recovery of voltage on a discharged capacitor is caused by "soakage," or dielectric absorption, which causes the dielectric of the capacitor to "remember" the voltage it was recently at. In high-voltage equipment, it is wise to install a 2W resistor of a few hundred kilohms across each large high-voltage filter capacitor to bleed off the charge and decrease the chance of shocks (**Ref 1**).

The last problem with old vacuum-tube equipment is that the heat tends to dry up the capacitors' electrolyte, thus causing their capacitance to decrease. This decrease is evidenced by excessive ripple, or "hum," on various signals and, of course, on the power-supply output of unregulated supplies. Although I have presented these maladies as problems afflicting old equipment, you should consider them even in new designs.

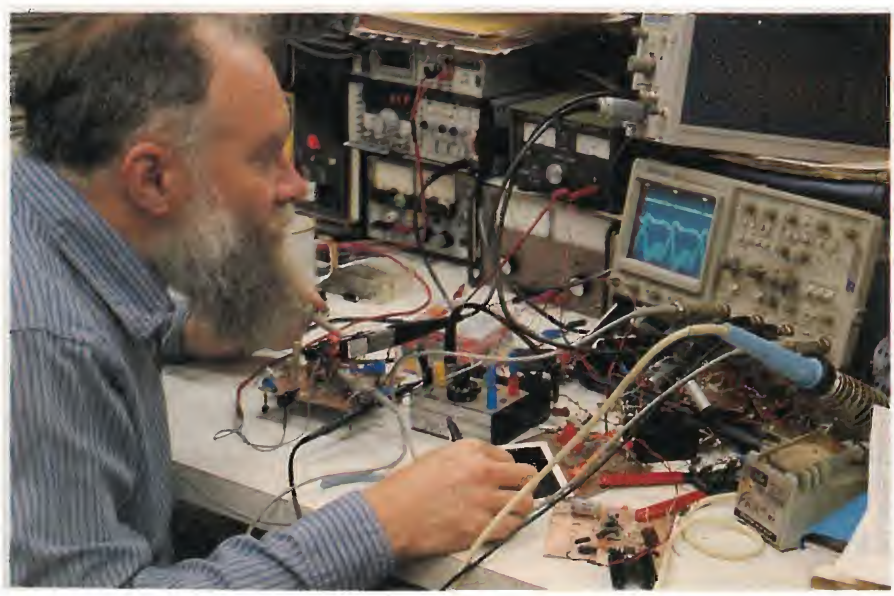
In modern power-supply designs, it is critical that you choose a filter capacitor whose effective series impedance is low at all rated temperatures. Otherwise the rms filter current multiplied by the resistive component of the series impedance can cause excessive self heating. And if the heat can't flow out of the capacitor, the temperature will rise and cause poor reliability. Excessive heating is one of the most common causes of failure in electrolytic capacitors.

For instance, at 120 Hz, which is the frequency of the ripple current flowing in the filter capacitors that follow a full-wave rectifier operated from a 60-Hz ac source, some manufacturers rate their capacitors at 2A rms for each 1000 μF. Because the rms current in the capacitor is nearly 2A rms when the dc output is 1A, this rating is consistent with the rule of thumb for an ordinary full-wave bridge rectifier: Provide at least 1000 μF of filter capacitance for each 1A of dc output. At 20 or 40 kHz, which is the ripple-current frequency in many switch-mode power-supply filters, the capacitor will have a higher series resistance. Thus, the capacitor won't be suitable for handling even 1A rms. If you insist on using a 120-Hz-rated capacitor as a filter in a switch-mode supply, you will probably have to contact the capacitor vendor for data or advice.

Of course, if you install an electrolytic capacitor with reversed polarity and apply working voltage, the reliability will be poor and the failure mode will probably be dramatic. So, please be careful working with big power supplies and big filter capacitors that store large amounts of energy. Wear protective goggles or glasses with safety lenses for protection because a capacitor in a high-energy supply might decide to blow up while you are peering at it. In fact, a friend of mine pointed out that a 6V electrolytic capacitor of even a few microfarads can blow out as explosively as a shotgun blast if you apply 6V dc of the wrong polarity or 6V ac to it. So, again, be very careful with your polar electrolytic capacitors.

**Nonpolar capacitors can be a bear**

You can buy nonpolar electrolytic capacitors made of either aluminum or tantalum. They are bigger and more expensive than ordinary, polar capacitors, so they are fairly uncommon. But, have you seen the little 3-leaded electrolytic types recently brought to market?



***That's funny,*** *it worked just fine the last time I tried it.*

The lead in the center is the positive terminal and the other two leads are negative. This configuration not only gives you lower inductance but also allows you to insert the device into a board two ways—and *both* are correct.

Tantalum capacitors have many characteristics similar to those of aluminum electrolytic capacitors; and, for the extra price you pay, you can get less leakage and somewhat lower series resistance. Designers often try out a timing circuit using a tantalum capacitor and a high-value resistor. But when they try to buy a tantalum capacitor with leakage guaranteed low enough to make the circuit work every time, they get quite angry when nobody is interested in selling such a device. Of course, if you were a manufacturer of tantalum capacitors and someone asked you to measure the leakage, you would refuse the business, too, because testing is so difficult. Even though this leakage is usually quite low, nobody wants to have to measure it in production.

Wound-film and stacked-film capacitors cover wide ranges, from small signal-coupling capacitors to large high-power filters. The different dielectrics are their most interesting ingredients. Often a designer installs a polyester capacitor (technically, polyethylene terephthalate, often called Mylar—a trademark of DuPont Corp) and wonders why something in the circuit is drifting 2 or 3% as the circuit warms up. What's drifting is probably the polyester capacitor; its TC of 500 to 800 ppm/°C is 10 times as high as that of a metal-film resistor.

If you give up on polyester and go to polystyrene, polypropylene, or Teflon, the TC gets better—about −120 ppm/°C. Polystyrene and polypropylene have low leakage and good dielectric absorption—almost as good as Teflon's, which is the best **(Ref 1).** But Teflon is quite expensive and much larger in package size than the other types. Be careful with polystyrene; its maximum temperature is +85°C, so you can damage it during ordinary wave soldering. Polycarbonate has a TC of 150 ppm/°C but has inferior soakage.

### Foiled again!

Now let's discuss the difference between a polyester foil capacitor and a metallized polyester capacitor. The foil capacitor is made of alternating layers of film and foil, where both the delicate film and the metal foil are just a couple of tenths of a mil thick. This construction makes a good capacitor at a nominal price and in a nominal size. The metallized-film capacitor is made with only a very thin film of polyester—the metal is deposited on the polyester. This construction leads to an even smaller size for a given capacitance and voltage rating, but the deposited metal is so thin that its current-carrying capacity is much less than that of the metal in the foil capacitor. If a pinhole short develops in the metallized-polyester capacitor's plastic film, the metal layer in the vicinity of the pinhole will briefly carry such a high current density that it will vaporize like a fuse and "clear" the short.

For many years, metallized polyester capacitors were popular in vacuum-tube television sets. These metallized capacitors would recover from pinhole flaws not just once but several times. However, at low voltages, the energy stored in the capacitors would often prove insufficient to clear a fault. Thus, the capacitors' reliability at low voltages was often markedly worse than it was at their rated voltage. You could safely use a cheap, compact, metallized-polyester capacitor in a 100V TV circuit but not in a 2V circuit. Fortunately, there are now classes of metallized-polycarbonate, metallized-polyester, and metallized-polypropylene capacitors that are reliable and highly suitable for use at both low and high voltages.

When the old metallized-polyester capacitors began to fail in a TV set, the "clearing" of the shorts would make the signals very noisy. Likewise, when used as audio coupling capacitors, "dry" tantalum capacitors would sometimes make a lot of noise as they "cleared" their leaky spots. These parts have therefore become unpopular for audio coupling. Similarly, you can use an electrolytic capacitor with a small reverse voltage—perhaps 0.5V—with no harm or problems. But a friend told me of a time an electrolytic capacitor used as an audio coupling capacitor with 2V of reverse bias produced all sorts of low-frequency noise and jitter. So, excess noise is often a clue that something is going wrong.

### Extended foil offers extensive advantages

Another aspect of the film capacitor is whether or not it uses "extended-foil" construction. The leads of many inexpensive wound-foil capacitors are merely connected to the ends of the long strip of metal foil. However, in an extended-foil capacitor, the foils extend out on each end to form a direct low-resistance, low-inductance path to the leads. This construction is well suited for capacitors that must provide low ESR (equivalent series resistance) in applications such as high-frequency filters. But if you substitute a capacitor without extended foil, the filter's performance will be

*It is critical to choose a filter capacitor whose effective series impedance is low at all rated temperatures.*

drastically degraded.

So there are several methods of construction and several dielectrics that are important for most capacitor applications. If an aggressive purchasing agent wants to do some substituting to improve cost or availability, the components engineer or design engineer may have to do a lot of work to make sure that the substitution won't cause problems. If a substitution is made, the replacement part is a good place to start looking for trouble. For example, a capacitor with higher-than-planned-for ESR can cause a feedback loop to oscillate—for example, when a capacitor without extended-foil construction is substituted for one with such construction. Substitution of capacitors with higher ESR than the designer intended can also cause filters to fail to properly attenuate ripple. Another consequence of excessive ESR is the overheating and failing of capacitors—capacitors may be passive components, but they are not trivial.

Not only does extended-foil construction lower a capacitor's ESR, it also lowers the component's inductance. As a friend pointed out, "Pease, you understand things really well if they are at dc or just a little bit faster than dc." I replied, "Well, that's true, but what's your point?" His point was that in RF circuits, and many other kinds of fast circuits, you should use capacitors and other components dressed closely together, so that the inductance is small and well controlled. He was absolutely right—the layout of a high-speed, fast-settling or a high-frequency circuit greatly affects its performance. Capacitors for such circuits must be compact and not have long leads. Ceramic and silvered-mica capacitors are often used for that reason.

Every year, billions of ceramic capacitors find their way into electronic products of all kinds. There are basically three classes of these parts: the "high-K" and "stable-K" types and the C0G or NP0 types.

The high-K types, such as those with a "Z5U" characteristic, give you a lot of capacitance in a small space—for example, $10^6$ pF in a 0.3-in. square that is 0.15-in. thick. That's the good news. The bad news is that the capacitance of parts with this Z5U characteristic drops 20% below the room-temperature value at 0 and 55°C; it drops 60% below the room-temperature value at −25 and +90°C. Also, the dielectric has a poor dissipation factor, mediocre leakage, and a mediocre voltage coefficient of capacitance. Still, none of these drawbacks prevents capacitors of this type from being used as bypass capacitors across the supply terminals of virtually every digital IC in the whole world. That's a lot of capacitors!

These ceramic capacitors have a feature that is both an advantage and a drawback—a typical ESR of 0.1Ω or lower. So, when a digital IC tries to draw a 50-mA surge of current for a couple of nanoseconds, the low ESR is a good feature: It helps to prevent spikes on the power-supply bus. However, when you have 10 ICs in a row and 10 ceramic bypass capacitors, you've got a long L-C resonator (**Fig 1**) with the power-supply bus acting as a low-loss inductor between each pair of bypass capacitors. When repetitive pulses excite this resonator, ringing of rather large amplitude can build up and cause an excessively noisy power-supply bus.

The standard solution is to add 2 μF of tantalum electrolytic bypass capacitors or 20 μF of aluminum electrolytic capacitors for every three to five ICs. The

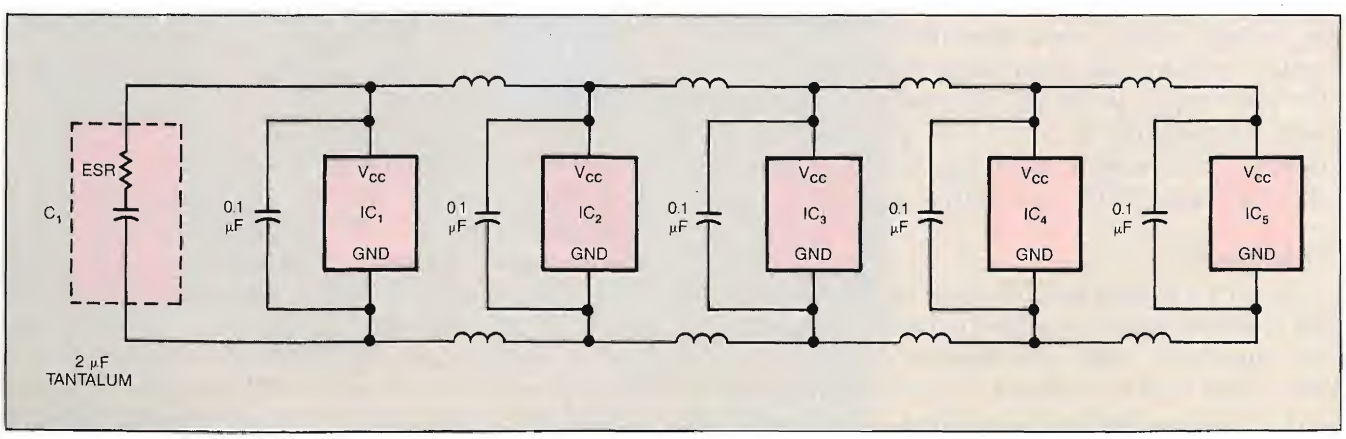



***Fig 1—Low ESR in a decoupling capacitor*** *is a 2-edged sword. Though a capacitor with low ESR stabilizes the supply bus when the ICs draw short-duration current spikes, the low dissipation encourages ringing by allowing the decoupling capacitance to resonate with the bus inductance. One cure is to place an electrolytic capacitor, such as $C_1$, across the bus. $C_1$'s ESR of approximately 1Ω damps the ringing.*

ESR of the electrolytic capacitors, typically 1Ω, is essential to damp out the ringing. I have read a few ads in which some capacitor manufacturers claim that their ceramic bypass capacitors are so good that ringing is no longer a problem, but I find the claims hard to believe. I invite your comments.

**ESR, friend or foe?**

Specifically, some capacitor manufacturers claim that the series resistance, $R_S$, is so low that you won't have a problem with ringing. But low $R_S$ would seem to exacerbate the ringing problem. Conversely, I've heard that one capacitor manufacturer is proposing to market ceramic capacitors whose series $R_S$ has a lower limit—a few ohms—to help damp out any ringing. I'm going to have to look into that. But if you have bypass capacitors with a very low $R_S$, you can lower the Q of the resonator you have inadvertently constructed around them by adding a resistor of 2.7 to 4.7Ω in series with each capacitor. Adding resistance in series with bypass capacitors might seem a bit silly, but it's a very useful trick.

High-K ceramic capacitors also can exhibit piezoelectric effects: When you put a good amount of ac voltage across them, they can hum audibly; if you rattle or vibrate them, they can kick out charge or voltage. (Other types can do the same thing, but high-K types are worse.) Be careful when using these capacitors in a high-vibration environment.

The capacitance of stable-K capacitors, such as X7R, typically decreases by 15% from the room-temperature value over the −55 to +125°C range. These capacitors are general-purpose devices and are usually available in the 100- to 10,000-pF range; in the larger packages, you can get as much as 300,000 pF. However, you can buy a 10,000-pF capacitor in either a high-K or a stable-K type; and you can't be sure of the kind you're getting unless you check the catalog and the part number.

The last type of ceramic capacitor was originally called "NP0" for Negative-Positive-Zero and is now usually called "C0G." The C0G capacitor is really a high-grade capacitor with a guarenteed TC of less than ±30 ppm/°C. Their dissipation factor, dielectric absorption, and long-term stability are not quite as good as those of Teflon capacitors but are comparable to those of other good precision-film capacitors. So, if you want to make a S/H circuit usable over the military temperature range, you'll find that C0G capacitors are more compact and less expensive then Teflon parts. Many, but not all, ceramic capacitors smaller than 100 pF are made with the C0G characteristic. You can get a 22,000-pF C0G capacitor in a 0.3-in.-square package.

Recently, a customer called me about a drift problem: His V/F converter had a poor TC, even though he said that he had put in a C0G 0.01-μF capacitor as the main timer. Troubleshooting by phone—it's always a wonderful challenge. I asked him, "This C0G-ceramic 0.01-μF capacitor . . . is it . . . as big as your little fingernail?" He said, "Oh no. It's a lot smaller than that." I replied, "Well, that's too small; it can't be a C0G." Problem solved.

One observed failure mode for ceramic capacitors can arise when the capacitor's leads are attached to the dielectric with ordinary, low-temperature solder. When the capacitor goes through a wave-solder machine, the lead may become disconnected from the capacitor. If this problem occurs, you'll have to switch to capacitors from a manufacturer that uses high-temperature solder.

**Don't forget silvered mica**

Silvered-mica capacitors have many features similar to C0G capacitors. They have low ESR and a TC of 0 to 100 ppm/°C. They can also work at temperatures above 200°C if assembled with high-temperature solder. Unfortunately, they have poor soakage characteristics.

A major problem with silvered-mica capacitors is their marking. The silvered-mica capacitors in old radios had completely inscrutable markings—six color dots. Some of the new ones have such odd codes that even if the marking on the capacitor hasn't rubbed off, you can never be sure whether "10C00" means 10, 100, or 1000 pF. You really need to use some kind of capacitance meter. Similarly, in the old days, some ceramic capacitors were marked in an inscrutable way. I remember two little capacitors both marked "15K." One was a 15-pF capacitor with a 'K' characteristic, and the other was a 15,000-pF capacitor—yet they were both the same size and had the same marking.

I must also mention that, in the past, you could buy a pretty good capacitor that had never been tested for its capacitance. About 99% of the time, they were excellent, reliable capacitors. But once in a while, some of the capacitors came through with a completely different value. One time I saw a whole box of "capacitors" in which the two leads were still made of one loop of wire that had not been snipped apart. Obviously, the manufacturer wasn't interested in testing and measuring these capacitors before sending them out the door.

*A 6V electrolytic capacitor of even a few microfarads can blow out as explosively as a shotgun blast if you apply 6V dc of the wrong polarity to it.*

So, if you are buying capacitors to a 1% AQL (Acceptance Quality Level) and not 0.1% or 0.01%, you should be aware that some low-priced parts have not even been sample tested.

**Variable capacitors have finite rotational lives**

Variable capacitors are usually made of low-K material with characteristics similar to those of C0G capacitors. Their performance is excellent. The dielectric doesn't cause much trouble, but the metal sliding contacts or electrodes on some types are very thin; after only a small number of rotations—hundreds or even dozens—the metal may wear out and fail to connect to the capacitance.

In general, capacitors are very reliable components; and, if you don't fry them with heat or zap them mercilessly, the small-signal ones will last forever and the electrolytic ones will last for many years. (Old oil-filled capacitors aren't quite that reliable and have probably been replaced already—at least they should have been replaced.) The only way you can have an unreliable capacitor is to use a type that is unsuitable for the task. And that's the engineer's fault, not the capacitor's fault. Still, some troubleshooting may be required; and if you recognize the clues that distinguish different types of capacitors, you've taken a step in the right direction.

What procedures are best for troubleshooting capacitors? I use two basic procedures, the first of which is the add-it-on approach. Most circuits are not hopelessly critical about capacitor values, as long as the capacitors' values are large enough. So, if there is a 0.01-μF capacitor that I suspect of not doing its job, I just slap another 0.01-μF capacitor across it. If the ripple or the capacitor's effect changes by a factor of two, the original capacitor was probably doing its job and something else must be causing the problem. But if I observe little or no change or a change of a factor of three, five, or ten, I suspect that capacitor's value was not what it was supposed to be. I pull the capacitor out and measure it. Of course, the capacitor substitution boxes I mentioned in the section on test equipment can be valuable here; they let me fool around with different values. But in critical circuits, the lead length of the wires going to the substitution box can cause crosstalk, oscillation, or noise pickup; so I may have

## But is this really troubleshooting?

When I passed the first draft of this article around to a few friends, one guy asked, "Why are you telling us all these things about weird capacitors? What does that have to do with troubleshooting?" I gave him the same answer I give you here: If you had a mediocre coupling capacitor and you didn't realize that it could keep on "leaking" for many seconds or minutes longer than a good coupling capacitor would, you wouldn't look for problems traceable to that capacitor. I cannot foresee every problem you will have in a circuit, but I can point out that similar-looking components can have startlingly different characteristics.

You can't learn about these characteristics from looking in books, or even in data sheets. So, if you get in trouble, I'm trying to suggest clues to look for to help you get out. Conversely, if you study these precautions and think about what can happen, you may be able to avoid getting into trouble in the first place. That's even better than being able to get out.

In fact, maybe some of the warnings I have presented here will explain why you once had a problem whose cause you could never figure out. Every once in a while, I learn something that stops me in my tracks: "That explains why the oscillator I made two years ago never worked right." If you stand on my shoulders, you may be able to get to places that neither of us could get to alone.

I certainly didn't figure out every one of these ideas by myself. I am passing along many ideas that I gleaned from other people's experience. Furthermore, I doubt if they invented all those ideas themselves. Surely, they benefited from other peoples' ideas that they picked up along the way. I am just trying to pass along insights that are not book learning but that I learned in the College of Hard Knocks. It may or may not be troubleshooting, but it's close enough for me.

*Be careful with polystyrene; its maximum temperature is +85°C, so you can damage it during ordinary wave soldering.*

to just "touch in" a single capacitor to a circuit.

Suppose, for example, that I have a polyester coupling capacitor that seems to be adding a big, slow "long tail" to my circuit's response. I don't expect the performance with the polyester capacitor to be perfect, but a tail like this one is ridiculous! So, I lift up one end of the polyester capacitor and install a polypropylene unit of the same value. I expect the new capacitor's characteristics to be a lot better than those of the old capacitor. If the tail gets a lot smaller, either my plan to use polyester was not a good one or this particular polyester capacitor is much worse than usual. It's time to check. But usually, I'd expect to find that the polypropylene capacitor doesn't make the circuit perform much better than the polyester capacitor did, and I'd conclude that something else must be causing the problem.

For either of these techniques to work, it is helpful to have a large stock of assorted capacitors. In our lab, we have several cartons of used—but not too badly beaten up—components left over from old experiments: One is a box of small mica and ceramic capacitors, one holds various electrolytic capacitors, and one is a tray of assorted wound-film capacitors. These boxes are extremely valuable because if I need an odd type, I can usually fish in one of those cartons and find something close. Or I can find some capacitors that give the right value if I parallel two or three of them. I can use these capacitors per the add-it-on or the substitution method to find out what my unhappy circuit is trying to tell me. In addition, I keep a couple of Teflon capacitors in my file cabinet for when I need a super-good capacitor.

A technique that nobody talks about but is as old as the hills is a favorite trick of mine. Sometimes it drives my technicians wild, but then they learn the trick and find it awfully useful. Let's say I want to compare a Mylar capacitor with a ceramic capacitor in a small, precision circuit. The technician starts to remove the Mylar capacitor and install the ceramic one. Wrong! Instead, remove one lead of the first capacitor and lift it up slightly. Then tack solder one end of the second capacitor to the circuit. At this point, neither capacitor is actually in the circuit—both capacitors are just waving in the breezes.

After the solder thoroughly cools down, I can use the springiness of the leads to let me "touch in" one of the capacitors or the other or both, as needed. It only takes a second to go from one mode to the other. (Of course, I'm assuming there's not enough voltage to "bite" my finger.) If I actually desolder and resolder the capacitors and allow enough time for these temperature-sensitive components to cool off, I'll probably forget what the difference between them looks like. So, this technique can save a lot of time and greatly facilitates A-B comparisons—it lets me use my eyeball to evaluate the nuances of small performance changes.

Of course, if I have two or three of these spring-loaded options at one time and they begin to get wobbly, it may be time to tack solder down the ones that I am not actively pursuing. In general, though, this technique is extremely valuable, and I've never seen it in any book. Use it with my compliments. It works with diodes, resistors, and transistors, too. Just make sure that solder flux doesn't prevent the spring-loaded component lead from contacting the conductor. And make sure that your finger doesn't add a lot of capacitance, impedance, or noise into the circuit. If you do have this problem, push on the component with the edge of a fingernail instead of a finger. A fingernail adds less than ½ pF. EDN

## Reference

1. Pease, R A, "Understand capacitor soakage to optimize analog systems," *EDN*, October 13, 1982, pg 125.

## Author's biography

*For more information about Bob Pease, see the* ***box****, "Who is Bob Pease, anyway?" in the January 5, 1989, edition of EDN.*

Article Interest Quotient (Circle One)
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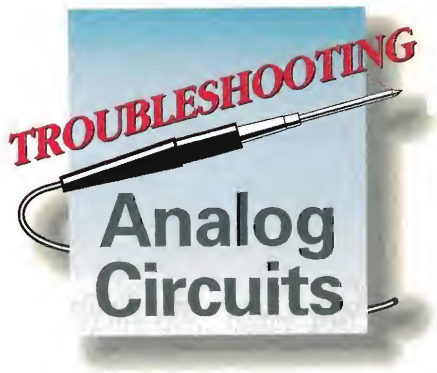


**PART 5**

# Follow simple rules to prevent material and assembly problems

*In addition to your choice of components, the materials you use to assemble your circuit will have an impact on how well it performs. This article, part 5 of a 5-part series on troubleshooting passive components, covers what you need to know to solve the occasional problems caused by pc boards, solder, connectors, wire, and cable. Also covered is pc-board layout—a poor layout can cause more than occasional problems; it can completely determine how well your circuit works.*

Robert A Pease, *National Semiconductor Corp*

Some of the topics discussed in this troubleshooting series so far may have seemed obvious. But far too often it is this information that engineers overlook, and it is this information that can make troubleshooting so much easier. So, be careful not to overlook the obvious. Don't assume that your pc-board materials or layout don't matter or that wire characteristics don't differ; you'll find that pc boards, connectors, wire, and cable cause problems when you least expect it.

First of all, the use of the term "printed-circuit board" is a misnomer; these days, almost every board is an etched-circuit board. But I'll continue to use the abbreviation "pc board" because it's a familiar term.

There are six basic troubles you can get into with pc boards:

- The board is the wrong material.
- The quality of the vendor's board is so bad that there are opens or shorts in the board or, worse yet, intermittent connections in the plated-through holes.
- The foil starts to peel off the board because of mistreatment.
- You were so concerned with cost that you neglected to specify a layer of solder mask; you ended up with a board full of solder shorts.
- The surface of the board is leaky or contaminated.
- Your circuit layout is such that signals leak and crosstalk to each other or controlled-impedance lines are interfering, thus causing reflections and ringing.

**Avoid pc-board problems at the outset**

The fixes for these problems, and ways to avoid them in the first place, are fairly straightforward:

These days, the G10 and G11 fiberglass-epoxy materials for pc boards are quite good and reasonably priced. Trying to use phenolic or "fishplate" is not economical in most cases. Conversely, a special high-temperature material or an exotic material or flexible substrate may be justifiable. If you don't have an ex-

*Don't overlook problems that can be caused by pc boards, connectors, and cable; they are often the source of your circuit's trouble.*

pert on these materials, the pc-board maker or the manufacturer of the substrate material can usually provide some useful advice. (See **Table 1** for a comparison of pc-board materials.)

In some RF applications, phenolic material has advantages over glass epoxy; it has a lower dielectric constant and superior dimensional stability. And for ultrabroadband oscilloscope probes, glass epoxy has a definite disadvantage due to mediocre dielectric absorption, especially if the epoxy has not been properly cured.

As for quality, there is almost never an excuse for buying your boards from a vendor whose products are of unknown quality. "Low cost" would be one poor alibi; "Can't get acceptable delivery from our normal vendor," would be another. One time, to meet a rush contract, we had to build circuits on boards made in our own lab facilities. I had never had trouble before using these boards for prototyping, so I was surprised when I began the troubleshooting and found that an apparently good board occasionally had a short between two buses.

Close inspection with a magnifying glass showed a hairline short about 3 mils wide, which was caused by a hair that fell onto the artwork. You would never ask a printed-circuit foil that narrow to carry 20 mA, but this narrow short would carry 200 mA before blowing out. Similarly, we found hairline opens: The ground bus was broken in two or three places by a tiny 4-mil gap, just barely visible to the naked eye. After several hours of fiddling around, opening shorts, and shorting opens, we vowed not to be caught by such poor workmanship again.

As for the third problem, don't let hamfisted engineers or technicians beat up a good pc board with the overenthusiastic or misguided application of a soldering iron. That's sure to lift the foil.

Solder mask, the subject of the fourth problem, is almost always worthwhile, as many people have learned. Without it, the admirable tendency of solder to bridge things together, which is wonderful in most instances, becomes disastrous.

When a pc board comes from its manufacturer, it is clean and exhibits high impedance. Sometimes a board starts out leaky, but normally a board doesn't begin to leak until you solder it or wash it with a contaminated solvent—the fifth problem. (For a description of two methods for testing leakage, see **box,** "Looking for leakages.").

Recently, a customer had a problem with a design using an LM317 regulator in which the impedances were fairly low. After just a few minutes of operation, the output of the LM317 would start drifting badly. The cause turned out to be not the LM317 or the

## TABLE 1—PC-BOARD LAMINATE MATERIALS

| TYPE | MANUFACTURER | DIELECTRIC CONSTANT (AT 1 MHz) | DISSIPATION FACTOR (AT 1 MHz) | VOLUME RESISTIVITY (MΩ-cm) | SURFACE RESTIVITY (MΩ) | MAXIMUM TEMPERATURE (°C) | COMMENTS |
|---|---|---|---|---|---|---|---|
| XXXPC | GENERIC | 4.1 | 0.032 | $5 \times 10^6$ | $5 \times 10^4$ | +125 | LOW COST, PAPER-BASED PHENOLIC; POOR MECHANICAL STRENGTH |
| CEM-1 | GENERIC | 4.5 | 0.025 | $1 \times 10^8$ | $5 \times 10^7$ | +130 | STANDARD, ECONOMICAL |
| CEM-3 | GENERIC | 4.7 | 0.020 | $1 \times 10^8$ | $5 \times 10^7$ | +130 | SIMILAR TO CEM-1 BUT CAN BE PUNCHED |
| G-10 | GENERIC | 4.75 | 0.023 | $5 \times 10^8$ | $4 \times 10^8$ | +130 | COMPARABLE TO CEM-3 |
| F4486 | OAK | 3.5 | 0.02 | $1 \times 10^9$ | $3 \times 10^6$ | N/A | FLEXIBLE |
| FR-4 | GENERIC | 4.9 | 0.018 | $1 \times 10^8$ | $5 \times 10^7$ | +130 | SIMILAR TO CEM-3 BUT FIRE RETARDENT PER UL-94-V-0 |
| GT-522 | KEENE | 2.5 | 0.0010 | $1 \times 10^7$ | $1 \times 10^7$ | +260 | TEFLON IS GOOD FOR HIGH TEMP, HIGH SPEED |
| GX-527 | KEENE | 2.5 | 0.0019 (AT 10 GHz) | $1 \times 10^7$ | $1 \times 10^7$ | +260 | CHARACTERIZED FOR HIGH FREQUENCY |
| HI-3003 | TECHNOPLY | 4.5 | 0.020 | $3 \times 10^7$ | $5 \times 10^6$ | +250 (10,000 HOURS) | POLYIMIDE |
| 3003-QUARTZ | TECHNOPLY | 3.6 | 0.004 | $5 \times 10^9$ | $8 \times 10^7$ | +250 (10,000 HOURS) | COMPARABLE TO CEM-3 |

resistors or capacitors, but the flux buildup where the board hadn't been washed after soldering. In this case, the impedance of the scorched flux was as low as 500Ω when measured across a 0.1 × 1-in. area of the pc board. So, even if you are not trying to achieve $10^{12}\Omega$ of leakage resistance, you should still observe rudimentary standards of cleanliness, or even your simplest circuits won't work right.

Similarly, one of our pc boards designed for a S/H circuit was yielding $10^{11}\Omega$ of leakage resistance, which was unacceptable. We tried cleaning the board with every organic solvent but had no luck. Finally, I took a few boards home and set them in the dishwasher along with the normal charge of Calgonite. After a full wash and rinse cycle, I pulled out the boards, banged them to shed most of the water beads, and set them in my oven to dry at 160°F. The next day, they checked out at the more acceptable value of $10^{13}\Omega$. I have used this technique several times on leaky pc boards and sockets, and it works surprisingly well.

Make sure the designers of your pc board keep a list of rules to avoid troubles. For example, if your circuit has a high-impedance point and you suspect leakage might be a problem, don't run that high-impedance trace beside a power-supply foil—guard it with a stripe of ground foil between the two. A dozen times I have heard an engineer say, "The resistivity of this glass-epoxy material is $10^{14}\Omega$-cm, so you can't possibly have a resistivity of $10^{12}\Omega$ from your summing point to the rest of the world . . . . " Then, I demonstrate that the measured impedance is typically a lot more than the specifications say, but I agree that I wouldn't dare count on that fact. So, I guard the summing point to ground with a grounded foil surrounding the critical nodes on both the top and bottom of the boards.

With the addition of these grounds, the circuit can perform well even under worst-case humidity conditions. After all, the internal volume of the glass-epoxy insulator is always dry, whereas the surface is the place where you can easily get a leakage problem due to dirt or moisture. That's where you have to prevent the leakage. Of course, crosstalk and high-frequency coupling problems are caused by adjacent foil locations and are cured by the same guarding and shielding just discussed to prevent foil leakages. To help you plan a good layout, think about what dv/dt and di/dt will do in a poor layout.

The field of pc-board layout is a subject unto itself. But there are some things you can do or add to a layout that will make testing the circuit much easier. Thoughtful designers have a store of these tricks, but I bet very few write them down. In my world, the unwritten rules are the ones that are broken, so we are trying to write them down. I recommend that all designers write down a list of their good ideas. Some layout tips from my list are

- Make sure that the signals you need access to for troubleshooting or analysis are easy to find and probe. Make a hole in the solder mask for accessibility.
- Include a silkscreen layer of labels in your layout artwork showing each component and its reference designation. It's also a good idea to label numbered test nodes and the correct polarity of diodes and electrolytic capacitors.
- Arrange the signal paths so that if you are desperate, you can easily break a link and open a loop, be it analog or digital.
- Many modern pc boards have multiple layers and sophisticated patterns of ground planes, power-supply buses, and signal flows. Troubleshooting such a board requires specialized techniques and skills and all sorts of "maps," so you don't get lost or confused. Make an effort to be sure that all the board's nodes are accessible, not hidden or buried on an inside layer.
- When possible, leave adequate space around components, especially ones that are more likely to fail and need to be replaced. Such components might be part of circuits that lead off the board and into the realm of ESD transients and lightning bolts and, thus, might occasionally fail.
- Locate delicate components away from the edge of boards, where they might be damaged by rough handling.
- Be careful using eyelets to connect different layers of foil on your pc board.

Years ago, plated-through holes were considered risky, so we used eyelets to connect the top and bottom foils. When these eyelets went through temperature cycling, the thermal stresses would cause the eyelets to lift the foil right off the boards. Even in the last year, I have seen advertisements that sing out the praises of eyelets on pc boards, so be careful when using them. These days, plated-through holes are quite reliable, but I still like to use them in conjunction with eyelets when I have enough room. It just makes me feel more comfortable.

More important than these layout conveniences is

*You can ease the testing of your circuit by including such items as test points and labels in your layout.*

that your layout not interfere with and, if possible, enhance the expected performance of the circuit. Most designers of digital circuits are aware that with high-speed logic, you can't just run the fast signals any old way. You have to treat these signal paths as transmission lines and route them carefully. So, whether with printed-circuit foils or wire-wrapped conductors, most designers have learned to build digital circuits that work well.

However, I have seen cases in which a wise digital designer had to add a few linear circuits to one corner of a mostly digital pc board. If the designer makes bad guesses about how to wire an op amp, the linear circuits may oscillate or work poorly. And, the availability of wire-wrap connections makes it tempting for the board designer to make a neat-looking layout with all the op amps and comparators and feedback resistors and capacitors in neat rows. Unfortunately, this neatness causes some critical interconnections to be a couple of inches apart. And then the designer is puzzled

## Looking for leakages

When you have a leaky board or a slightly less-than-infinite-impedance connector or insulator, how do you test for leakage? There are basically two ways to measure leakage current.

The approach I have used for many years is to connect a couple of transistors as a wide-range, logarithmic, current-to-voltage detector across the feedback path of a low-bias-current op amp. These days, I'm not using vacuum tubes—I have graduated to an LMC660, as shown in the circuit of **Fig A.** I calibrated the meter with a hand-drawn scale to sense currents ranging from 1 pA to 1 mA and −1 pA to −1 mA **(Fig B).** As long as the air conditioning doesn't break down, I know my calibration won't drift much more than 10 or 20%, which is adequate to tell me which decade of current I am working in.

It's true that the DVM approach shown in **Fig C** has a little more accuracy and perhaps more resolution; but it is easily fooled by noise, and the digital readout doesn't show trends well. And, if you want to cover a wide range of currents, you have to plug in

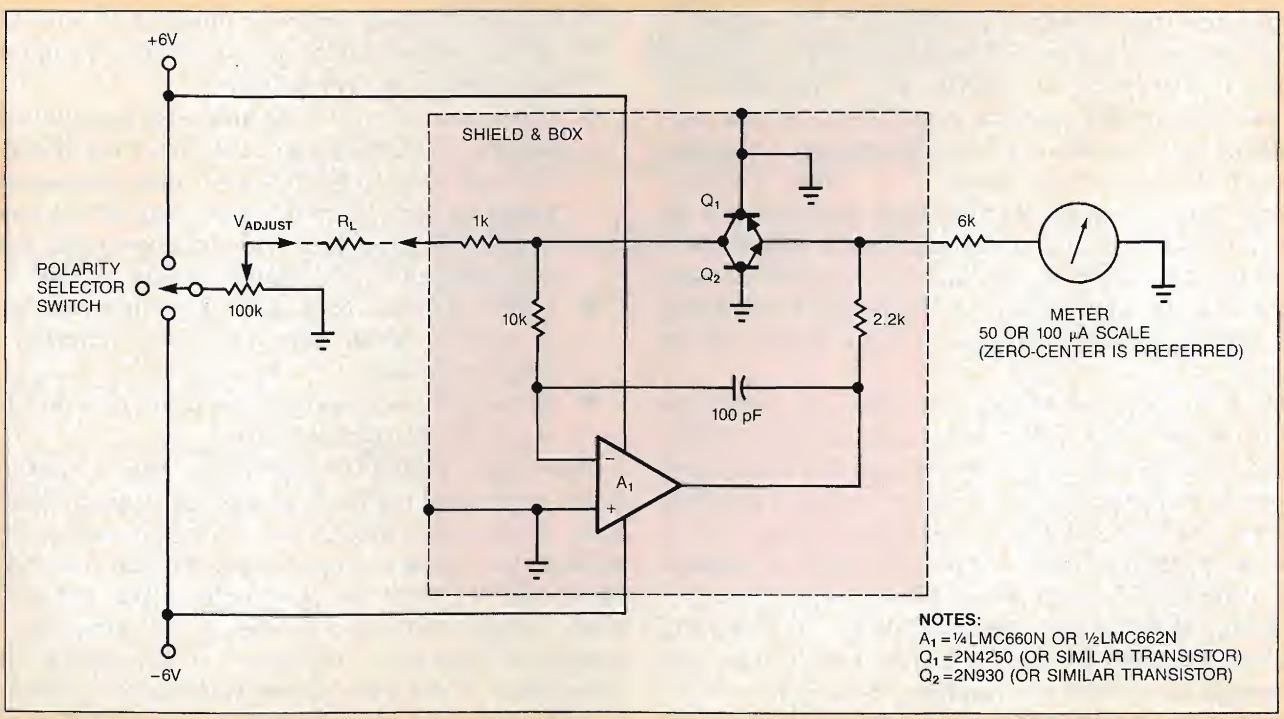


***Fig A—You can use this circuit to test your board for leakage current.*** *The transistors are connected across the op amp's feedback path in such a way that they act like a current-to-voltage detector.*

as to why the amplifiers and comparators are oscillating so badly.

So, pc-board designers should be made aware that the layout of linear ICs can be quite critical. The 2-in. spacing that you would never allow, for example, between a digital IC and its bypass capacitor is the same 2-in. spacing that makes an op amp unhappy when its inverting or noninverting input has to travel that distance to various resistors. As I will explain in future articles on active-circuit troubleshooting, there are good reasons to keep those summing-point foils short, neat, and compact.

Engineers often assume that a printed-circuit trace has virtually no resistance and no IR drop. But, when you run large currents through a foil run, you will be unpleasantly surprised by the IR drop you'll see. The classic example is a layout where the signal ground for a preamplifier is mixed and shared with the ground return path for the power supply's bridge and filter capacitor. This return path will see ampere-size surges

different resistors or wait for the DVM to autorange, which is not my idea of fun. On the other hand, you can find a DVM almost anywhere, so this approach is easy to implement.

Whichever detector you use, apply a reasonable voltage across the unknown impedance and see where the leakage gets interesting. This method can also be used for diodes and transistor junctions. The op-amp circuit is not recommended for measuring the leakage of large-value capacitors. Neither is the DMV approach because of the slow charging of the large capacitance and soakage, or dielectric absorption, effects. But, if you're desperate and start out with a low value of $R_{sense}$, you can eventually get some approximate measurements.

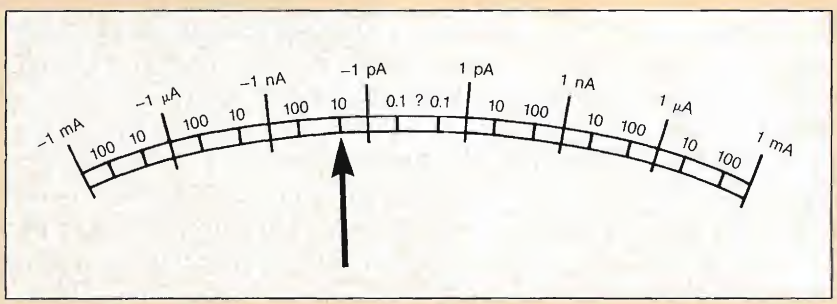


***Fig B—You can calibrate the logarithmic-current-meter** circuit of **Fig A** to sense currents between −1 mA and −1 pA and between 1 pA and 1 mA.*

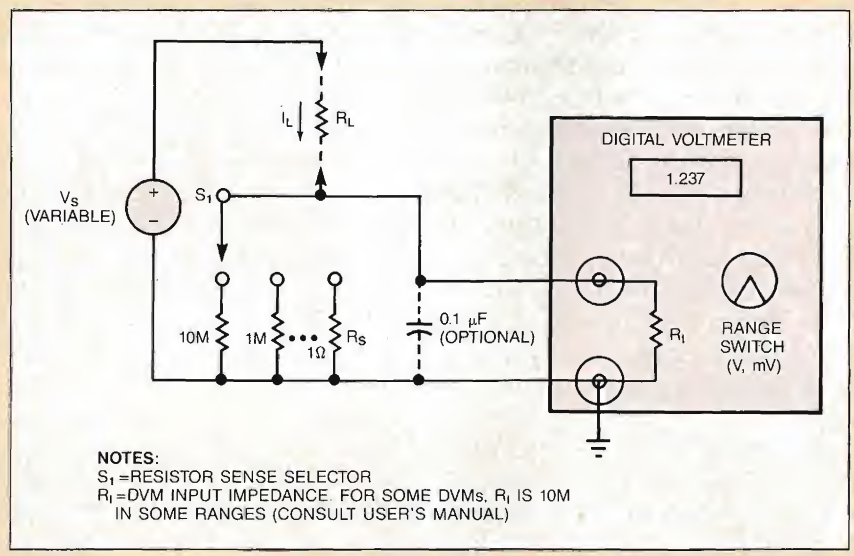


***Fig C—The DVM approach is an alternative** to the approach illustrated in **Fig A** for testing leakage. You can calculate the leakage current from Ohm's Law: $V_S = I_L \times R_S$, or $I_L = V_S / R_S$.*

*Leakage troubles usually start after the board has been soldered or washed with a contaminated solvent.*

120 times per second. Needless to say, the preamplifier won't have "low noise" until the path for the current surges is essentially divorced from the preamp's ground. For precision work, your pc-board layout must include well-thought-out ground paths for your sensitive circuitry.

When you think about it, separating power-supply grounds that carry lots of current from voltage-sensing circuitry is similar to Kelvin connections, which are commonly used in test instruments. A Kelvin connection uses four wires: one pair of leads is meant to carry current and the other pair senses voltage across a device. Keeping the idea of Kelvin connections in mind when designing your pc board will help you optimize your grounding scheme.

**Avoid cold-soldered joints**

I have a few comments to add about solder; most of the time we take it for granted. You'll normally use ordinary rosin-core tin-lead solder. If you avoid jiggling the soldered joint as it is cooling, you won't get a cold-soldered joint. But you should know what a cold-soldered joint looks like and how much trouble one can cause in a critical circuit. I feel sort of sad that today's young people aren't building kits for electronic equipment. In the old days, you could learn all about cold-soldered joints before you got into industry. But with modern wave-soldering equipment, it's fairly easy to avoid cold-soldered joints.

If for some reason you have acid-core solder around—it's mainly used for plumbing and is not found in most electronics labs, for good reason—keep it strictly segregated from ordinary rosin-core solder. Acid will badly corrode conductors. Also, keep specialty solders such as high-temperature solder, low-temperature solder, silver solder, and aluminum solder in a separate place to avoid confusion.

Printed-circuit boards aren't the only assembled component you'll have to contend with while trying to make circuits work. In Tracy Kidder's Pulitzer Prize-winning book, *The Soul of a New Machine* (**Ref 1**), one of the crucial moments occurs when the engineers explain to a management team that their new computer has a flaw that occurs only rarely but is driving them to distraction. One of the managers stands thoughtfully for a while and then reaches over and warps the main board: Scrunch, scrunch. To the horror of the project engineers, the scrunching correlates with the terrible intermittent problem. When the main board's DIP sockets were replaced, the problem disappeared.

Like a faithful dog, a connector is expected to do its job without question, and it usually does. However, on the rare occasion when one does go bad, the connector usually becomes intermittent before it fails utterly. Fortunately, many engineers and technicians learn early on that the way to check an intermittent problem is to make it reveal itself when the board's connector is plugged in and out while the power is on.

But don't all the instruction books say that you shouldn't plug in the board with the power on? Sure. But I've never gotten into more trouble plugging a board into a hot connector than the trouble I've gotten out of. There may be some boards that are destroyed or damaged by this method, but they are in the distinct minority and should be studied. One way to help avoid problems is to make the ground fingers on a printed-circuit edge connector stick out longer than the other fingers. Thus, ground will be established before any other connection. Still, if you have a board that tends to latch up because the power-supply sequencing may be improper, you have to be prepared to stop plugging the board into that hot socket—fast.

**Learn by fiddling and tweaking**

There are many situations that can foul things up, but we all tend to learn more from fiddling around with things, tweaking and unplugging, than by purely cerebral processes. Once I had a technician who thought that DIP sockets should not be secured in place by tack soldering but by glue. This technique worked fine for a while, but occasionally the sockets would act like an open circuit on one pin or another. To solve the problem, we used an old technique. We traced the circuit coming into the IC, and it was fine. We traced the signal coming out of the IC; nothing. Then, we traced the signals on the pins of the DIP itself; the signals were not the same at all. I finally realized that the glue was getting into the internal voids of the socket and preventing the IC's pin from making a true connection.

We banned the glue from that task, and the problem went away, mostly. Still, both before and after that time, we have seen sockets that just failed to connect to an IC's pin. You merely have to probe to the pin of the IC itself, not just to the socket, to nail down this possibility. Sometimes, the pin goes into the socket and actually fails to connect; but, more often than not,

the pin is simply bent under the package.

There is one other kind of problem you can have with a socket, as a friend of mine recounted. He was trying to troubleshoot a very basic op-amp circuit whose waveforms did not make sense. After several minutes, he turned his circuit over and realized he had forgotten to plug an op amp into the socket. This example leads us to McKenna's Law, named after an old friend of mine: "You can't see it if you don't look at it." We invoke this law when we discover that we forgot to plug in a line cord or connect something. A vital part of troubleshooting is realizing that we are all at the mercy of McKenna's Law when we get absent-minded.

Connectors and sockets usually do more good than harm. They permit you to check options and perform experiments that may seem absurd and preposterous, yet are instructional and life-saving. Once a friend was in the throes of a knockdown-dragout struggle to troubleshoot a fast A/D converter. He had tried many experiments, but a speed problem eluded him. He asked me if he should try a socket for a critical high-speed component. At first, I was aghast. But, after I thought about it and realized that the socket would add barely 1 pF of capacitance, I said, "Well, OK, it may not do much harm."

The addition of the socket led to the realization that the speed problem was critically correlated with that component, and the problem was soon solved. The socket that might have caused terrible strays actually caused almost no harm and, in fact, facilitated the real troubleshooting process. If nothing you do leads in an encouraging direction and you have a half-baked notion to tell your technician to install a socket, that may be the best idea you have all day. The socket may do very little harm and could lead to many experiments, which might give you the vital clue that puts you on the track of the real culprit.

Now, I'll add a few pithy comments about wire and cable. Not all wire is the same. For example, when I first got a job in electronics, I was having a lot of trouble with Teflon-insulated wire. The wires would often break right at the point where the solder stopped. After several engineers assured me that all wire was the same and suggested that I was just imagining things, I was ready to scream.

Finally, I found an engineer who admitted that cable manufacturers couldn't put individually tinned wires into a Teflon insulator, as they do with plastic-insulated

***Whether you are designing a pc board or an IC,*** *your circuit's layout is critical to its performance. For certain designs, you'll need to carefully consider the placement of each component, as Pease and his group demonstrate.*

wire. At the temperatures at which the Teflon is extruded, the solder would all flow together, thus making the stranded wire a solid wire. Instead, cable manufacturers use silver-plated wire strands for Teflon-insulated wire. With this type of wire, solder tends to wick up into the strands, thus making the wire quite brittle. Once I understood the wire's structure, I was able to solve my problems by adding strain relief for any bends or pulling stresses.

As I mentioned in the section on equipment for troubleshooting, the ordinary plastic-insulated single-conductor wire that is used in telephones has just the right stiffness to make good twisted-pair wire for making capacitors with values of 1, 2, or 5 pF. The wire doesn't have a Teflon dielectric, but it's good enough for most applications.

**Consider your wire type**

Shielded or coaxial cables, such as RG58U, RG174, shielded twisted pairs, and other special flat cables, all have their place in the job of getting signals from here to there without undue attenuation or crosstalk. When you have a large number of wires mindlessly bundled together and you don't have any bad crosstalk, you're witnessing a miracle. Often you have to unbundle the wires and separate the offending ones or the sensitive, delicate signals from the rest. Also, you may end up rewiring some or all of the wires into shielded cables.

Remember, Teflon is a good insulator, but air is even better. If you have to add struts, standoffs, or spacers to make sure that the critical wires stay put, go right ahead. If you have problems, the wire manufacturers can give you some advice.

Conversely, just as you use Teflon or air when you need a superior insulator, you have to be careful to get your best conductances. A friend who is an amateur radio operator says that many kinds of problems in RF circuits arise because nuts and bolts are used to make ground connections. If a lock washer or star washer is not included, the mechanical connection can loosen, the ground impedances will change with every

little stress or strain, and nasty intermittent electrical problems will result. So, a major factor in the reliability of these circuits is ensuring the integrity of all bolted joints by always including star washers. And, make sure that wires and connectors do not get so loose as to hurt the reliability of your circuit or system.

When you use shielded cable, should you ground the shield at one end or at both ends? Many cases call for a ground at the receiving end of the cable, but there are cases in which the shield is the main ground return. Neither way is necessarily bad, but be consistent. Likewise, in the design and the execution of the design, avoid ground loops, which can cause weird noise problems. In my systems, I build my analog ground system completely separate from the digital ground and make sure that the case or package ground is also strictly divorced. Then, I add one link from the analog ground to the digital ground and another link to the case or chassis. This technique works well for me, and I recommend it.

It is a little-known fact that some coaxial cable can degrade just sitting on the shelf. Types whose codes end in "U," such as "RG-58U," have an "uncontaminating" outside shield. In contrast, RG-58 might have an outside shield with superior physical characteristics, but it could, over time, degrade the electrical properties of the cable—specifically, its UHF attenuation. So, even in something as simple as a wire, there may be more problems than meet the eye. EDN

## References

1. Kidder, Tracy, *The Soul of a New Machine*, Avon Books, New York, NY, 1981.

## Acknowledgments

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## Author's biography

*For information about Bob Pease, see the* ***box,*** *"Who is Bob Pease, anyway?" in the January 5, 1988, edition of EDN.*

Article Interest Quotient (Circle One)
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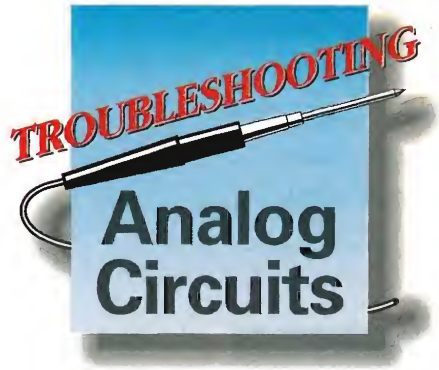



PART 6

# Active-component problems yield to painstaking probing

*Continuing the previous 5-part series on troubleshooting passive parts, this article from the prolific pen of Bob Pease presents the opening salvo of a 7-part series on troubleshooting active components. Bob begins with the simple stuff: diodes and rectifiers, optically coupled devices, solar cells, and batteries. Subsequent articles will expose the mysteries of more complex active devices.*

Robert A Pease, *National Semiconductor Corp*

Even the simplest active devices harbor the potential for causing baffling troubleshooting problems. Consider the lowly diode. The task of a diode sounds simple: to conduct current when forward biased and to block current when reverse biased while allowing negligible leakage. That task sounds easy, but no diode is perfect, and their imperfections are fascinating.

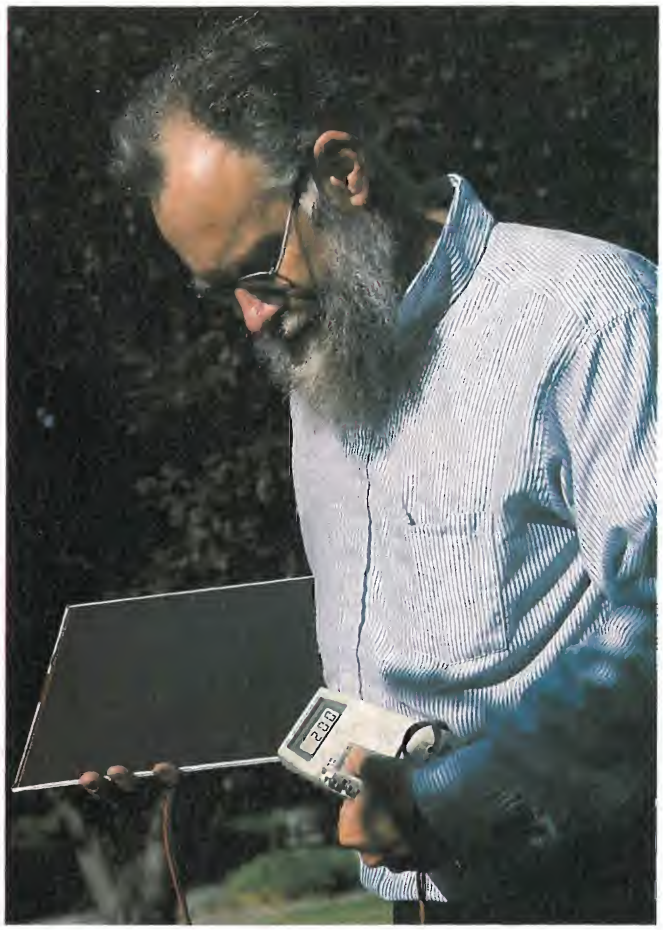
All diodes start conducting current exponentially at low, microampere levels, and the slope of their I/V curves is given by the equation: $g \approx (38.6\ mS/mA) \times I_F$, where mS = millisiemens = millimhos and $I_F$ = forward current. But as the current levels increase, most diodes tail off to $g = (19\ mS/mA) \times I_F$ and then the conductance per milliampere gets even lower due to ohmic and other nonlinear factors. Therefore, at a large forward current, a diode's forward voltage, $V_F$, will be considerably larger than predicted by simple theory—and larger than desired. Of course, some rectifiers—depending on their ratings—*can* handle large currents from amperes to kiloamperes; but the $V_F$s of all diodes, no matter what their ratings, err from the theoretical at high current levels.

These days, Schottky diodes have smaller $V_F$s than ordinary pn diodes. However, even germanium diodes and rectifiers still have their following because their low $V_F$s are similar to the Schottky's.

High-speed and ultrahigh-speed (sometimes also called high-efficiency) silicon rectifiers that are designed for switching-regulator and other high-frequency applications are also available. They don't have quite as low $V_F$s as Schottky diodes and are not quite as fast, but they are available with high reverse-voltage ratings and thus are useful for certain voltage and power levels and certain circuit topologies that impress large flyback voltages on diodes.

When you reverse bias these various diodes, ah, that is where you start to see wild dissimilarities. For example, the reverse-current specification, $I_{REV}$, for many types of diodes is 25 nA max at 25°C. When you measure them, many of these devices actually have merely 50 or 100 pA of leakage. But the popular 1N914 and its close cousin, the 1N4148, actually *do* have about 10 or 15 nA of leakage at room temperature because of their gold doping. So although these diodes are inex-

*Although 1N914s are inexpensive and popular, don't use them in low-leakage circuits because they're much leakier than other diodes with the same leakage specs.*



Photographs by Peggi Willis

***With a solar-cell array, you** can make electricity when the sun shines.*

pensive and popular, it's wrong to use them in low-leakage circuits since they're much leakier than other diodes with the same leakage specs.

Why, then, do some low-leakage diodes have the same mediocre 25-nA leakage spec as the 1N914? Diode manufacturers set the test and price at the level most people want to pay because automatic test equipment can test at the 25-nA level—but no lower—without slowing down. If you want a diode characterized and tested for 100 pA, you have to pay extra for the slow-speed testing. Of course, high-conductance diodes such as Schottkys, germaniums, and large rectifiers have much larger reverse leakage currents than do signal diodes.

If you want a very low-leakage diode, use a transistor's collector-base junction instead of a discrete diode (**Ref 1**). You can easily find such "diodes" having less than 1-pA leakage even at 7V or 10 pA at 50V. Although this low leakage is not guaranteed, it's usually quite consistent. However, this diode generally doesn't turn ON or OFF very quickly.

Another source of ultralow-leakage diodes are the 2N4117A and the PN4117A, -18A, and -19A. These devices are JFETS with very small junctions, so leakages well below 0.1 pA are standard—1.0 pA max, guaranteed, for a $0.40 part.

"Computer diodes" like the 1N914 are popular because they turn OFF quickly—in just a few nanoseconds—much faster than low-leakage diodes. What isn't well known is that the faster diodes not only turn OFF fast, they *usually* turn ON fast. For example, when you feed a current of 1.0 mA toward the anode of a 1N914 in parallel with a 40-pF capacitance (20 pF of stray capacitance plus a scope probe or something similar), the 1N914 usually turns ON in less than 1 nsec. Thus, the $V_F$ has only a few millivolts of overshoot.

But with some diodes—even 1N914s or 1N4148s from some manufacturers—the forward voltage may continue to ramp up past the expected dc level for 10 to 20 nsec before the diode turns ON; this overshoot of 50 to 200 mV is quite surprising (**Fig 1**). Even more astonishing, the $V_F$ overshoot may get worse at low repetition rates but can disappear at high repetition rates (**Fig 1b** through **d**).

I spent several hours once discovering this particular peculiarity when a frequency-to-voltage converter suddenly developed a puzzling nonlinearity. The trickiest part of the problem with the circuit's diodes was that diodes from an earlier batch had not exhibited any slow-turn-on behavior. Further, some diodes in a batch of 100 from one manufacturer were as bad as the diodes in **Figs 1b** and **1c**. Other parts in that batch and other manufacturers' parts had substantially no overshoot.

When I confronted the manufacturers of the faulty diodes, they at first tried to deny any differences but at length admitted that they had changed some diffusions to "improve" the product. One man's "improvement" is another man's poison. Thus, you must always be alert for production changes that may cause problems. When manufacturers change the diffusions or the process or the masks, they may think that the changes are minor, but these changes could have a major effect on your circuit.

Many circuits, obviously, require a diode that can turn ON and catch, or clamp, a voltage moving much faster than 20V/μsec. Therefore, if you want any consistency in, for example, a circuit with pulse detectors,

you'll need to qualify and approve only manufacturers whose diodes turn ON consistently. So, as with any other unspecified characteristic, be sure to protect yourself against bad parts by first evaluating and testing and then specifying the performance you need.

One "diode" that does turn ON and OFF quickly is a diode-connected transistor. A typical 2N3904's emitter-collector diode can turn ON or OFF in 0.1 nsec with negligible overshoot and less than 1 pA of leakage at 1V, or less than 10 pA at 4V. However, this diode can only withstand 5 or 6V of reverse voltage, and most emitter-base junctions start to break down at 6 or 8V. Still, if you can arrange your circuits for just a few volts, these diode-connected transistors make nice, fast, low-leakage diodes. Their capacitance is somewhat more than the 1N914's 1 pF.

If you keep LEDs in the dark, they make an impressive, low-leakage diode because of the high bandgap voltage of their materials. Such LEDs can exhibit less than 0.1 pA of leakage when forward-biased by 100 mV or reverse-biased by 1V.

Of course, you don't have to reverse bias a diode a lot to get a leakage problem. One time I was designing a hybrid op amp, and I specified that the diodes be connected in the normal parallel-opposing connection across the input of the second stage to avoid severe overdrive (**Fig 2**). I thought nothing more of these diodes until we had the circuit running—the op amp's

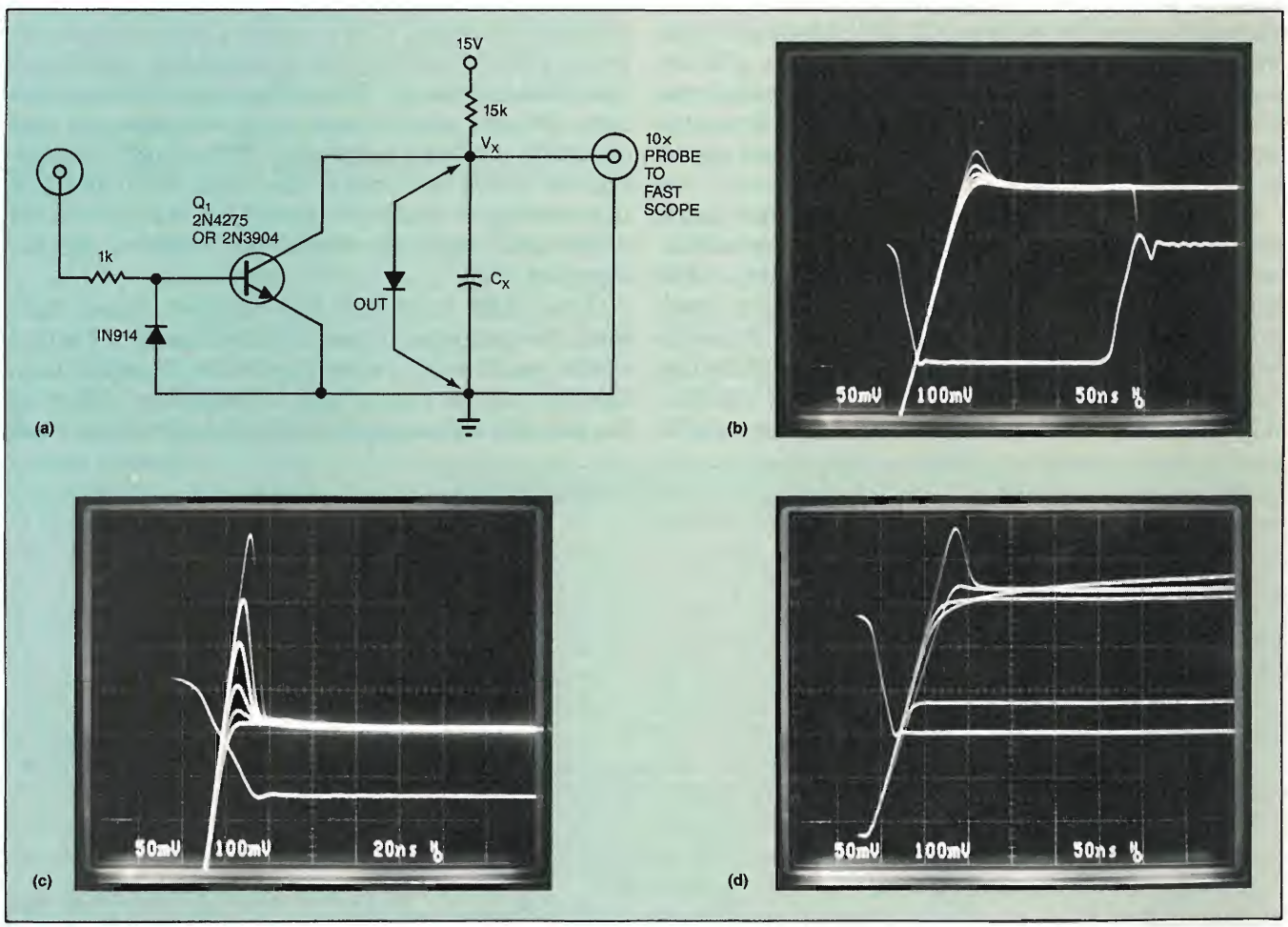



***Fig 1—In this diode-evaluation circuit (a),*** *transistor $Q_1$ simply resets $V_X$ to ground periodically. When the transistor turns OFF, $V_X$ rises to about 0.6V until the diode starts conducting. In* **b,** *when $dV_X/dt$ is 8V/μsec, this 1N4148 overshoots as much as 140 mV at input frequencies below 10 kHz before it turns ON. At higher frequencies—120, 240, 480, 960, and 1920 kHz—as the repetition rate increases, the overshoot shrinks and disappears. Maximum overshoot occurs when $f_{IN} \leq 7$ kHz. In* **c,** *when $dV_X/dt$ increases to 20V/μsec, this same 1N4148 overshoots as much as 450 mV at 7 kHz but only 90 mV at 480 kHz and negligible amounts at frequencies above 2 MHz. In* **d,** *various diode types have different turn-on characteristics. The superimposed, 120-kHz waveforms are all invariant with frequency, except for the bad 1N4148.*

*Always be alert for production changes that may cause problems.*

voltage gain was falling badly at 125°C. Why? Because the diodes were 1N914s, and their leakage currents were increasing from 10 nA at room temperature to about 5 μA at the high temperature. And—remember that the conductance of a diode at zero voltage is approximately (30 to 40 mS/mA)×$I_{LEAKAGE}$. That means each of the two diodes really measured only 6 kΩ.

Because the impedance at each input was only 6 kΩ, the op amp's gain fell by a factor of four, even though the diodes may have only been forward or reverse biased by a millivolt. When we substituted collector-base junctions of transistors for the diodes, the gain went back up where it belonged.

You cannot safely assume that the impedance of a diode at zero bias is high if the junction's saturation current is large. For example, at 25°C a typical 1N914 will leak 200 to 400 pA even with only one millivolt across it. Therefore, a 1N914 can prove unsuitable as a clamp or protection diode—even at room temperature—despite having virtually no voltage biased across it.

How can diodes fail? Well, if you were expecting a diode to turn ON and OFF, but it does something unexpected—of the sort I have been mentioning—that unexpected behavior may not be a failure, but it could sure cause *trouble*. Further, you can kill a diode by applying excessive reverse voltage without limiting the current or by feeding it excessive forward current. When a diode fails, it tends to short out, becoming a small blob of muddy silicon rather than an open circuit. I did once see a batch of 1N4148s that acted like thermostats and went open circuit at 85°C, but such cases are rare.

One of the best ways to kill a diode is to ask it to charge up too big a capacitor during circuit turn on. Most rectifiers have maximum ratings for how much current they can pass on a repetitive and on a nonrecurring basis. I've always been favorably impressed by the big Motorola (Phoenix, AZ) books with all the curves of safe areas for forward current as a function of time and repetition rate. These curves aren't easy to figure out at first, but after a while they're fairly handy tools.

Manufacturers can play tricks on you other than changing processes. If you expect a diode to have its arrow pointing toward the painted band (sometimes called the cathode by the snobbish) and the manufacturer put the painted band on the wrong end, your circuit won't work very well. Fortunately reverse-marked diodes are pretty rare these days. But just this morning, I heard an engineer call the pointed end of the diode an anode, which led to confusion and destruction. Sigh . . .

Once I built a precision test box that worked right away and gave exactly the right readings until I picked up the box to look at some waveforms. Then the leakage test shifted way off zero. Every time I lifted up the box, the meter gave an indication; I thought I had

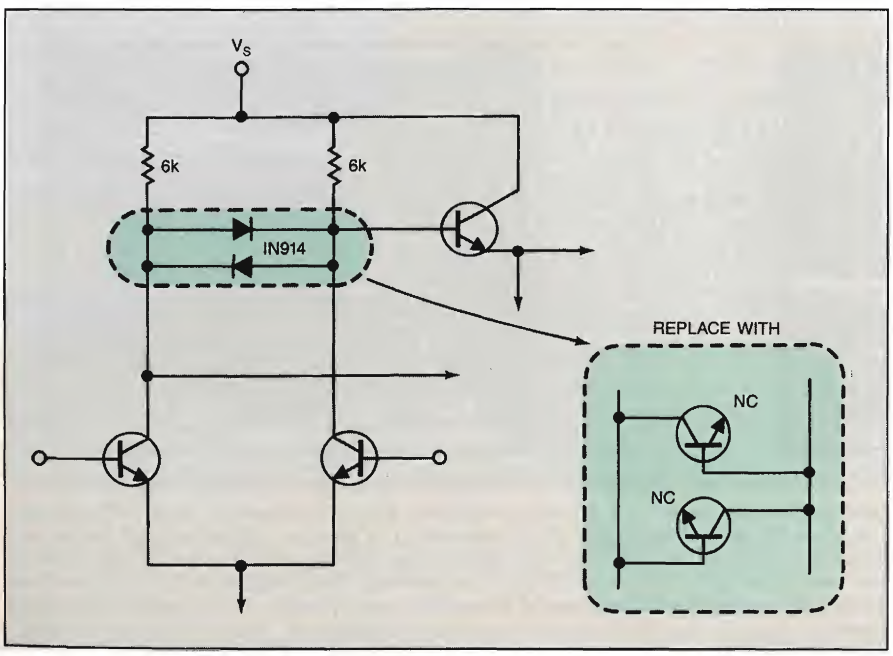



***Fig 2—Even though the diodes in the first stage** of this op amp are forward or reverse biased by only a millivolt, the impedance of these diodes is much lower than the output impedance of the first stage or the input impedance of the second stage at high temperatures. Thus, the op amp's gain drops disastrously.*

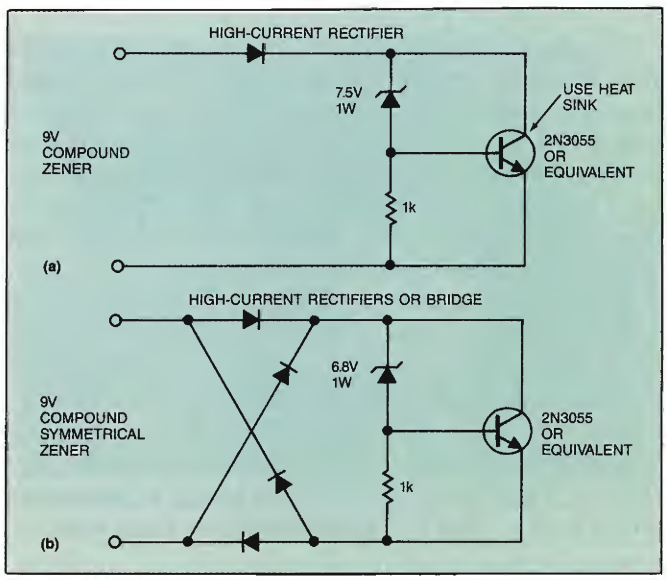



***Fig 3—The power rating of this compound Zener (a)*** *is that of the power transistor. The second compound Zener,* ***(b),*** *is almost the same as* ***a*** *but acts as a symmetrical, matched, double-ended compound Zener.*

designed an altimeter. After some study, I localized the problem to an FD300, whose body is a clear glass DO-35 package covered with black paint. This particular diode's paint had been scratched a little bit, so when I picked up the test box, the light shone under the fixture and onto the diode. Most of these diodes didn't exhibit this behavior; the paint wasn't scratched on most of them.

To minimize such problems, I recommend the following strategies:

- Have each manufacturer's components specifically qualified for critical applications. This is usually a full-time job for a components engineer, with help and advice from the design engineer and consultation with manufacturing engineers.
- Establish a good relationship with each manufacturer.
- Require that manufacturers notify you when, or preferably before, they make changes in their products.
- Keep an alternate source qualified and running in production whenever possible.

My boss may gripe if I say this too loudly, but it is well known that having two good sources is better than having one. The argument that "One source is better than two" falls hollow on my ears. Two may be better than seven or eight, but one is *not* better than two.

Just about all diodes will break down if you apply too much reverse voltage, but Zener diodes are *designed* to break down in a predictable and well-behaved way. The most common way to have problems with a Zener is to starve it. If you pass too little current through a Zener, it may get too noisy. Many Zeners have a clean and crisp knee at a small reverse-bias current, but this sharp knee is not guaranteed below the rated knee current.

Some Zeners won't perform well no matter how carefully you apply them. In contrast to high-voltage Zeners, low-voltage (3.3 to 4.7V) Zeners are poor performers and have poor noise and impedance specs and bad temperature coefficients—even if you feed them a lot of current to get above the knee, which is very soft. This is because "Zeners" at voltages above 6V are really avalanche-mode devices and employ a mechanism quite different from and superior to the low-voltage ones, which are real Zener diodes. At low-voltage levels, band-gap references, such as LM336s and LM385s, are popular because their performance is good compared with low-voltage Zeners.

Zener references with low temperature coefficients, such as the 1N825, are only guaranteed to have low temperature coefficients when operated at their rated current, such as 7.5 mA. If you adjust the bias current up or down, you can sometimes tweak the temperature coefficient, but some Zeners aren't happy if operated off bias. Also, don't test your 1N825 to see what its "forward-conduction voltage" is because in the "forward" direction, the device's temperature-compensating diode may break down at 70 or 80V. This breakdown damages the device's junction, degrades the device's performance and stability, and increases its noise.

And before you subject a Zener to a surge of current, check its derating curves for current vs time, which are similar to the rectifiers' curves mentioned earlier. These curves will tell you that you can't bang an ampere into a 10V, 1W Zener for very long.

If you do need a Zener to conduct a surge of current, check out the specially designed surge-rated Zener devices—also called transient-voltage suppressors—from General Semiconductor Industries Inc (Tempe, AZ). You'll find that their 1W devices, such as the 1N5629 through 1N5665A, can handle a surge of current better than most 10 or 50W Zeners. If you need a *really* high-current Zener, a power transistor can help out **(Fig 3)**.

As mentioned earlier, a diode tends to fail by becom-

*If you want a really low-leakage diode, use a transistor's collector-base junction instead of a discrete diode.*

ing a short circuit when overpowered, and Zeners cannot absorb as much power as you would expect from short pulses. How dreadful; but, can IC designers serendipitously take advantage of this situation? Yes!

The $V_{OS}$ of an op amp usually depends on the ratio of its first-stage load resistors. IC designers can connect several Zeners across various small fractions of the load resistor. When they measure the $V_{OS}$, they can decide which Zener to short out—or zap—with a 5-msec, 0.3-to-1.8A pulse. The Zener quickly turns into a low-impedance (~1Ω) short, part of the resistive network shorts out, and the $V_{OS}$ improves.

In its LM108, National Semiconductor (Santa Clara, CA) first used Zener zapping, although Precision Monolithics (Santa Clara, CA) *talked* about Zener zapping first and used it extensively later on. Although Zener zapping is a useful technique, you have to be sure that nobody discharges a large electrostatic charge into any of the pins that are connected to the Zener zaps. If you like to Zap Zeners for fun and profit, they really do make a cute lightning flash in the dark when you zap them. Otherwise, be careful *not* to zap them.

These Zener zaps are also becoming popular in digital ICs under the name of "vertical fuses" or "antifuses." If an IC designer uses platinum silicide instead of aluminum metallization for internal connections, the diode resists zapping.

Once I needed 100 LEDs, so I bought 200 LEDs from the cheapest supplier. I hoped to find some good ones and maybe just a few units that were weak or performed poorly, which I could use for worst-case testing. I lost out; every one of the 200 was of uniformly good intensity. In a variation on Murphy's Law, worst-case parts will typically appear only when you are depending on having uniform ones.

So long as you don't fry LEDs with your soldering iron or grossly excessive milliamps of current, LEDs are awfully reliable these days. I have a thermometer display on my wall, which has 650 inexpensive, plastic-packaged LEDs. These LEDs have amassed 30,000,000 device-hours with just one failure. The only problem I ever have with LEDs is trying to remember which lead is "plus"—I just rederive it, every time.

## Optoisolators

An optoisolator usually consists of an LED and a sensitive phototransistor to detect the LED's radiation. In the course of working with the cheaper 4N28s, I've found it necessary to add circuitry to achieve moderate speeds. For example, if you tailor the biases per **Fig 4,** you can usually get a 4N28's response up toward 50 kHz; otherwise the devices can't make even 4 kHz reliably. The trick is decreasing the phototransistor's turn-off time by using a resistor from pin 4 to pin 6.

I've evaluated many different makes and lots of

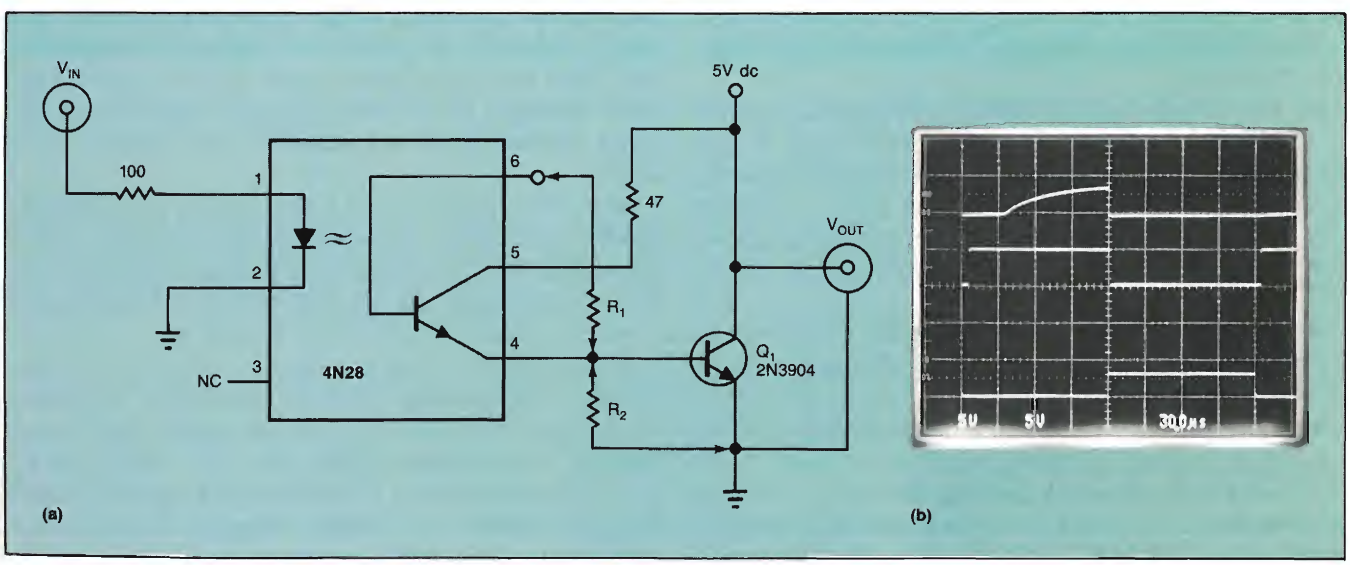



***Fig 4—Adding $R_1$ and $R_2$ to the** inexpensive 4N28 optoisolator lets it handle faster signals with less delay—5 µsec vs 60 µsec. The scope photo's bottom trace is an input waveform, the top trace is the circuit's output without $R_1$ and $R_2$, and the center trace is the output with $R_1$=2 MΩ and $R_2$=1 kΩ.*

***Maintaining a healthy battery*** *involves careful attention to charging, discharging, and temperature.*

4N28s and have found widely divergent responses. For example, the overall current gain at 8 mA can vary from 15 to 104%, even though the spec is simply 10% min. Further, the transfer efficiency from the LED to the photodiode varies over a range wider than 10:1, and the β of the transistor varies from 300 to 3000. Consequently, the transistor's speed of response, which is of course related to β and $f_{-3\ dB}$, would vary over a 10:1 range.

If your circuit doesn't allow for gains and frequency responses that vary so wildly and widely, expect trouble. For example, two circuits, one an optoisolated switching regulator (**Ref 2**) and the other a detector for 4- to 20-mA currents (**Ref 3**), have enough degeneration so that any 4N28 you can buy will work. I used to have a group of several "worst-case" 4N28s from various manufacturers that I would try out in prototypes and problem circuits. Unfortunately, I don't have the marginal devices anymore, but they were pretty useful.

Also, the data sheets for optoelectronic components often don't have a clear $V_F$ curve or list any typical values; the sheets list only the worst-case values. Therefore, you may not realize that the $V_F$ of an LED in an optoisolator is a couple hundred millivolts smaller than that of discrete red or infrared LEDs. Conversely, the $V_F$ of high-intensity, or high-efficiency, red LEDs tends to be 150 mV larger than that of ordinary red LEDs. And the $V_F$ of DEADs (a DEAD is a Darkness Emitting Arsenide Diode; that is, a defunct LED) is not even defined.

Once I was troubleshooting some interruptor modules. In these modules, a gap separated an infrared LED and a phototransistor. An interruptor—say a gear tooth—in the gap can thus block the light. I tested one module with a piece of paper and nothing happened—the transistor stayed ON. What was that again? It turned out that the paper could diffuse the infrared light but not completely attenuate it. A thin sheet of cardboard or two sheets of paper would indeed block the light.

### Solar cells

Extraneous, unwanted light impinging on the pn junction of a semiconductor is only one of many tricky problems you can encounter when you try to design and operate precision amplifiers—especially high-impedance amplifiers. Just like a diode's pn junction, a transistor's collector-base junction makes a good photodiode, but a transistor's plastic or epoxy normally does a very good job of blocking out the light.

When light falls onto the pn junction of any diode, the light's energy is converted to electricity and the diode forward biases itself. If you connect a load across the diode's terminals, you can draw useful amounts of voltage and current from it. For example, you could stack a large number of large-area diodes in series and use them for recharging a battery. The most unreliable part of this system is the battery. Even if you never abuse them, batteries don't like to be discharged a large number of cycles, and your battery will eventually refuse to take a charge.

So much for the charms of solar energy. It's much better to use a solar-powered night-light. Remember that one? A solar-powered night-light doesn't need a battery; it simply needs a 12,000-mile extension cord. To be serious, the most critical problem with solar cells is their packaging; most semiconductors don't have to sit out in the sun and the rain as solar cells do. And it's hard to make a reliable package when low cost is—as it is for solar cells—a major requirement.

In addition to packaging, another major trouble area with solar cells is their temperature coefficients. Just like every other diode, the $V_F$ of a solar cell tends to *decrease* at 2 mV/°C of temperature rise. Therefore, as more and more sunlight shines on the solar cell, it puts out more and more current, but its voltage could eventually drop below the battery's voltage whereupon charging stops. Using a reflector to get even more light onto the cell contributes to this temperature-coefficient problem. Cooling would help, but the attendant compli-

*A diode tends to short out when overpowered, and Zeners cannot absorb as much power from short pulses as you would expect.*

cations rapidly overpower the original advantage of solar cells' simplicity.

Lastly, I want to say a few things about batteries. The only thing that batteries have in common with diodes is that they are both 2-terminal devices. Batteries are complicated electrochemical systems, and large books have been written about the characteristics of each type (**Refs 4 through 9**). I couldn't possibly give batteries a full and fair treatment here, but I will outline the basics of troubleshooting them.

First, always refer to the manufacturer's data sheet for advice on which loads will yield optimal battery life. When you recharge a nickel-cadmium battery, charge it with a constant current, not constant voltage. And be sure that the poor little thing doesn't heat up after it is nearly fully charged. If you're subjecting your battery to deep-discharge cycles, refer to the data sheet or the manufacturer's specifications and usage manual for advice. Some authorities recommend that you do an occasional deep discharge, all the way to zero; others say that when you do a deep discharge, some cells in the battery discharge before the others and then get reversed, which is not good for them. I cannot tell you who's correct.

Sometimes a NiCd cell will short out. If this happens during a state of low charge, the cell may stay shorted until you zap it with a brief burst of high current. I find that discharging a 470-μF capacitor charged to 12V into a battery does a good job of opening up a shorted cell.

When you recharge a lead-acid battery, charge it to a float voltage of 2.33V per cell. At elevated temperatures, you should decrease this float voltage by about 6 mV/°C; again, refer to the manufacturer's recommendations. When a lead-acid battery is deeply discharged (below 1.8V per cell), it should be recharged right away or its longevity will suffer due to sulfation.

Be careful when you draw excessive current from a lead-acid battery; the good strong ones can overheat or explode. Also be careful when charging them; beware of the accumulation of hydrogen or other gases that are potentially dangerous or explosive.

And, please dispose of all dead batteries in an environmentally sound way. Call your local solid-waste-disposal agency for their advice on when and where to dispose of batteries. Perhaps some can be recycled.

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## Author's Biography

*For information about Bob Pease, see the box, "Who is Bob Pease, anyway?" in the January 5, 1989, edition of EDN.*

Article Interest Quotient (Circle One)
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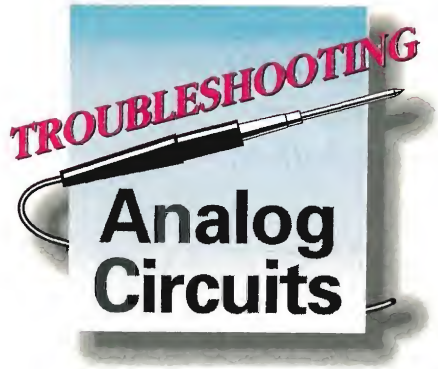



PART 7

# Rely on semiconductor basics to identify transistor problems

*Although transistors—both bipolars and MOSFETs—are immune to many problems, you can still have transistor troubles. Robust design methods and proper assumptions regarding their performance characteristics will steer you past the shoals of transistor disasters. After taking on 2-terminal devices in part 6, Bob covers these 3-terminal devices. Future parts will cover analog ICs.*

Robert A Pease, *National Semiconductor Corp*

Transistors are wonderful—they're so powerful and versatile. With a handful of transistors, you can build almost any kind of high-performance circuit: a fast op amp, a video buffer, or a unique logic circuit.

On the other hand, transistors are uniquely adept at causing trouble. For example, a simple amplifier probably won't survive if you short the input to the power supplies or the output to ground. Fortunately, most op amps include forgiving features, so that they can survive these conditions. When the μA741 and the LM101 op amps were designed, they included extra transistors to ensure that their inputs and outputs would survive such abuse. But an individual transistor is vulnerable to damage by excessive forward or reverse current at its input, and almost every transistor is capable of melting. So it's up to us, the engineers, to design transistor circuits so that the transistors do not blow up, and we must troubleshoot these circuits when and if they do.

A simple and sometimes not so obvious problem is installing a transistor incorrectly. Because transistors have three terminals, the possibility of a wrong connection is considerably greater than with a mere diode. Small-signal transistors are often installed so close to a printed-circuit board that you can't see if the leads are crossed or shorted to a transistor's can or to a pc trace. In fact, I recall some boards in which the leads were often crossed and about every tenth transistor was the wrong gender—pnp where an npn should have been, or vice versa. I've thought about it a lot, and I can't think of any circuits that work equally well when you install a transistor of the opposite sex. So, mind your Ps and Qs, your Ps and Ns, and your 2N3904s and 2N3906s.

In addition to installing a transistor correctly, you must design with it correctly. First of all, transistors require input protection. Most transistors can withstand dozens of milliamperes of forward base current but will die if you apply only a few volts. One of my pet peeves has to do with adding protective components. MIL-HDBK-217 has always said that a circuit's reliability decreases when components are added. Yet when you add resistors or transistors to protect an

*With a handful of transistors, you can build almost any kind of high-performance circuit, including fast op amps, video buffers, and unique logic circuits.*

amplifier's input or output, the circuit's reliability actually improves. It just goes to show that you can't believe everything you read in a military specification. For a specific criticism of the notion of computing reliability per MIL-HDBK-217, see **Ref 1.**

Similarly, if you pump current out of the base of a transistor, the base-emitter junction will break down. This reverse current—even if it's as low as nanoamperes or very brief in duration—tends to degrade the beta of the transistor, at least on a temporary basis. So in cases where accuracy is important, find a way to avoid reverse biasing the inputs.

Transistors are also susceptible to ESD. If you walk across a rug on a dry day, charge yourself up to a few thousand volts, and then touch your finger to an npn's base, it will probably survive because a forward-biased junction can survive a pulse of a few amperes for a small part of a microsecond. But, if you pull up the emitter of a grounded-base stage, you risk reverse-biasing the base-emitter junction. This reverse bias can cause significant damage to the base-emitter junction and might even destroy a small transistor.

When designing an IC, smart designers add clamp diodes, so that any pin can survive a minimum of ±2000V of ESD. Many IC pins can typically survive two or three times this amount. These ESD-survival design goals are based on the human-body model, in which the impedance equals 100 pF in series with 1500Ω. In discrete transistors, whose junctions are considerably larger than the small geometries found in ICs, ESD damage may not be as severe. But in some cases, ESD damage can still happen. Delicate RF transistors such as 2N918s, 2N4275s, and 2N2369s sometimes blow up "when you just look at 'em" because their junctions are so small.

Other transistor-related problems arise when engineers make design assumptions. Every beginner learns that the $V_{be}$ of a transistor decreases by about 2 mV per degree Celsius and increases by about 60 mV per decade of current. Don't forget about the side effects of these rules, or misapply them at extreme temperatures. Don't make sloppy assumptions about $V_{be}$s. For instance, it's not fair to ask a pair of transistors to have well-matched $V_{be}$s if they're located more than 0.1 in. apart and there are heat sources, power sources, cold drafts, or hot breezes in the neighborhood. Matched pairs of transistors should be glued together for best results.

I've seen people get patents on circuits that don't even work based on misconceptions of the relationships between $V_{be}$ and current. It's fair to assume that two matched transistors with the same $V_{be}$ at the same small current will have about the same temperature coefficient of $V_{be}$. But you wouldn't want to make any rash assumptions if the two transistors came from different manufacturers or from the same manufacturer at different times. Similarly, transistors from different manufacturers will have different characteristics when going into and coming out of saturation, especially when you're driving the transistors at high speeds. In my experience, a components engineer is a very valuable person to have around and can save you a lot of grief by preventing unqualified components from confusing the performance of your circuits.

Another assumption engineers make has to do with a transistor's failure mode. In many cases, people say that a transistor, like a diode, fails as a short circuit or in a low-impedance mode. But unlike a diode, the transistor is normally connected to its leads with relatively small lead-bond wires; so if there's a lot of energy in the power supply, the short will cause large currents to flow and vaporize the lead bonds. As the lead bonds deteriorate, the transistor will ultimately fail as an open circuit.

It's nice to design with high-beta transistors, and, "if some is good, more's better." But, as with most things in life, too much can be disastrous. The h-parameter, $h_{rb}$, equals $\Delta V_{be}/\Delta V_{cb}$ with the base grounded,

Photographs by Peggi Willis

***A curve-tracer can help you discern the difference** between a "good" transistor and a "bad" one. It can also help resolve the shape of the voltage-current curve of any nonlinear component.*

and many engineers have learned that as beta rises, so does $h_{rb}$. As $h_{rb}$ rises, the transistor's output impedance decreases; its Early voltage falls; its voltage gain decreases; and its common-emitter breakdown voltage, $BV_{ceo}$, may also decrease. (The Early voltage of a transistor is the amount of $V_{ce}$ that causes the collector current to increase to approximately two times its low-voltage value, assuming a constant base drive. $V_{Early}$ is approximately equal to $(1/h_{rb}) \times 26$ mV.) So, in many circuits there is a point where higher beta simply makes the gain lower, not higher.

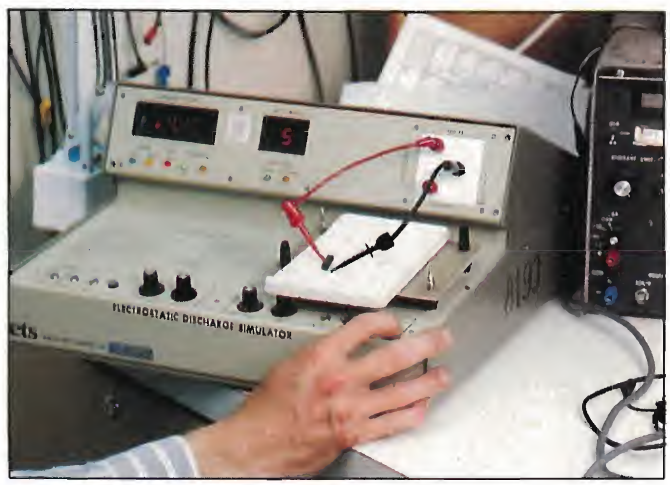
Another way to increase beta is to use the Darlington connection; but the voltage gain and noise may degrade, the response may get flaky, and the base current may decrease only slightly. When I was a kid engineer, I studied the ways that Tektronix made good use of the tubes and transistors in their mainframes and plug-ins. Those engineers didn't use many Darlingtons. To this day, I keep learning more and more reasons not to use Darlingtons or cascaded followers. For many years, it's been more important for many circuits to have matched betas than for them to have sky-high betas. You can match betas yourself or buy four or five transistors on one monolithic substrate, such as a monolithic transistor array.

One of the nice things about bipolar transistors is that their transconductance, $g_m$, is quite predictable. At room temperature, $g_m = 38.6 \times I_C$. Since the voltage gain is defined as $A_V = g_m \times Z_L$, computing it is often a trivial task. You may have to adjust this simple equation in certain cases. For instance, if you include an emitter-degeneration resistor, $R_e$, the effective transconductance falls to $1/(R_e + g_m^{-1})$. $A_V$ is also influenced by temperature changes, bias shifts in the emitter current, hidden impedances in parallel with the load, and the finite output impedance of the transistor.

For a given operating current, field-effect transistors normally have much poorer $g_m$ than bipolar transistors do. You'll have to measure your devices to see how much lower. Additionally, the $V_{gs}$ of FETs can cover a very wide range, thus making them hard to bias.

Also be aware that although the transconductance of a well-biased transistor is quite predictable, beta usually has a wide range and is not nearly as predictable. So you have to watch out for adverse performance if the beta is too low or too high and causes shifts in your operating points and biases.

JFETs became popular 20 years ago because you could use them to make analog switches with resistances of 30Ω and lower. JFETs also made good op amps with lower base currents than bipolar devices, at least at moderate or cool temperatures. The BiFET process made it feasible to make JFETs along with bipolars on a monolithic circuit. It's true that the best BiFET inputs are still slightly inferior to the best bipolar ones in terms of voltage-offset temperature coefficient, long-term stability, and voltage noise. But these BiFET characteristics keep improving because of improved processing and innovative circuit design. As a result, BiFETs are very close to bipolar transistors in terms of voltage accuracy and offer the advantage of low input current.

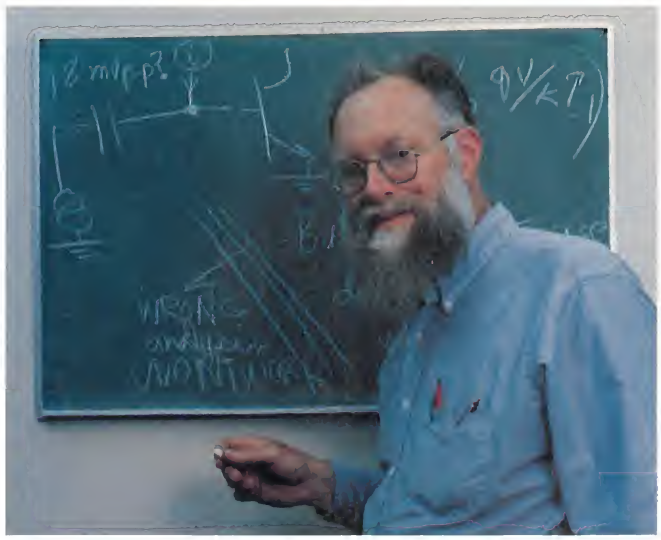



***When you hit a component or circuit with a pulse of ESD,*** *you can never be sure what kind of trouble you'll get—unless you've already tested it with an ESD simulator.*

I recall working on a hybrid circuit that had some JFETs whose gate connections were supposed to be through the back of the dice. I found that some of the dice didn't have proper metallurgical processing, which caused some strange behavior. Initially, the gate acted as if it were connected and would act that way for a long period of time. Then, the gate would act like an open circuit with as much as 1V of error between the actual gate and the bottom of the die. The gate would remain disconnected until a voltage transient restored the connection for another week! The intermittency was awful because nothing would speed up the 1-week cycle-to-failure time. So, we had to go back and add definite lead bonds to the gate's bond pad on the top of the chip, which we had been told was unnecessary. Ouch!

When designing hybrids, you need to make sure to

*Transistors are powerful and versatile, but they're also uniquely adept at causing trouble.*



***Using equations to analyze circuits*** *can sometimes help you define a problem. But if the equations are inapplicable, they do a lot more harm than good. This circuit is a version of a patented circuit that was cleverly designed to the highest levels of confidence using equations. The fact that it doesn't work is a mere footnote—except to the engineer who has to troubleshoot it.*

connect the substrate of a chip to the correct dc level. The bottom of a FET chip is usually tied to the gate, but the connection may be through a large and unspecified impedance. You have to be a pretty good chemist or metallurgist to be sure that you don't have to add a bond to the gate's metal. A bipolar-transistor die's substrate is the collector. Most linear and digital IC substrates are tied to the negative supply. Exceptions include the LM117 and similar adjustable positive regulators—their substrate is tied to $V_{out}$. The LM196 voltage regulator's substrate is tied to the positive supply voltage, $V_s$, as are the substrates of the MM74HC00 family of chips and most of the dielectrically isolated op amps from Harris. So, be aware of your IC's substrate connection. If an LM101AH op amp's metal can bumps against ground or $V_s$, you have a problem. Similarly, you shouldn't let an HA2525's case bump against ground or $-V_s$.

MOSFETs are widely used in digital ICs but are also very popular and useful in analog circuits, such as analog switches. Op amps with MOSFET inputs do well in the general-purpose op-amp market. MOSFETs have a bad reputation for excessive noise, but new devices, such as the LMC662, demonstrate that clean processing can cure the problem, thus making MOSFETs competitive with BiFETs. Just be careful not to let ESD near the inputs. MOSFETs do have protection diodes and may be able to withstand 800V, but they can't survive 2000V. If you work with unprotected devices, such as the 3N160, you must keep the pins securely shorted until the device is soldered into its pc board in which the protection diodes are already installed. I do all of that and wash the transistor package with both an organic solvent and soap and water. And, I keep the sensitive gate circuits entirely off the pc board by pulling the gate pin up in the air and using point-to-point wiring. Air, which is a superior dielectric, is also a good insulator (**Ref 2**). So far, I haven't had any blown inputs or bad leakages—at least nothing as bad as 10 fA.

On the other hand, when using CMOS digital ICs, I *always* plug them into live sockets; I *never* use conductive foam; and I *never* wear a ground strap on my wrist. And I've *never* had any failures—with one exception. One time I shuffled across a carpeted floor and pointed an accusatory finger at a CMOS IC. There was a small crack of ESD—probably 5000V—followed by a big SNAP as the IC blew out and crowbarred the entire power supply. Since ESD testing is done with the power OFF, if you did some tests with the power ON, you might get some messy failure modes like the one I just mentioned. Always be wary of any devices that manufacturers claim are safe from ESD.

### Power transistors may hog current

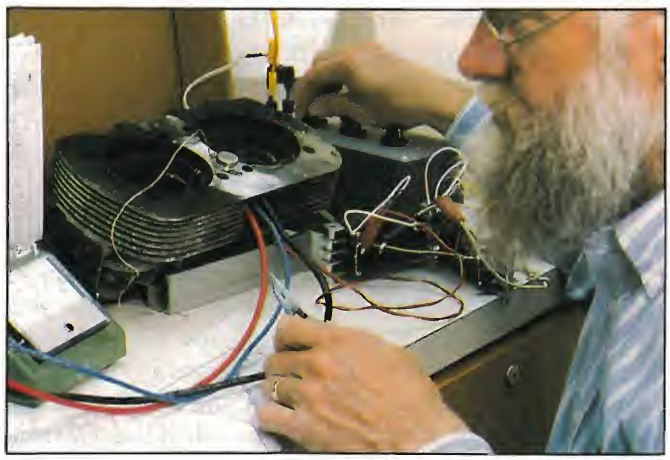
As you build a bipolar transistor bigger and bigger, you may be tempted to go to extremes and make a huge power transistor. But there are practical limitations. Soon, the circuit capacitances cause oppressive drive requirements, and removing the heat is difficult. Still, no matter how big you build power transistors, people will find a use for them. Their most severe problem is secondary breakdown, which is what happens when you drive a transistor outside its safe operating area.

When you operate a power transistor at very high currents and low voltages, the emitter resistance of the device—which includes the resistance of the emitter metal and the inherent emitter resistivity—can cause enough $I \times R$ drop to force the entire emitter and its periphery to share the current. Now, let's halve the current and double the voltage. The amount of dissipation is the same, but the $I \times R$ drop is cut in half. Now continue to halve the current and double the voltage. Soon you'll reach a point where the ballasting (**Fig 1**) won't be sufficient, and a hot spot will develop at a high-voltage point. The inherent decrease of $V_{be}$

causes an increase of current in one small area. Unless this current is turned OFF promptly, it will continue to increase unchecked. This "current hogging" may cause the area to melt or crater. The designers of linear ICs use ballasting, cellular-layout, and thermal-limiting techniques, all of which can prevent harm in these cases (**Ref 3**). Discrete transistors may someday include these features.

Fortunately, many manufacturers' data sheets include permitted safe-area curves at various voltages and for various effective pulse widths. So, it's possible to design reliable power circuits with ordinary power transistors. The probability of an unreliable design or trouble increases as the power level increases, as the adequacy of the heat sink decreases, and as the safety margins shrink. For example, if the bolts on a heat sink aren't tightened enough, the thermal path degrades and the part can run excessively hot.

High temperature *per se* doesn't cause a power transistor to fail. But, if the drive circuitry was designed to turn a transistor ON and only a base-emitter resistor is available to turn it OFF, then at a very high temperature, the transistor will turn itself ON and there will be no adequate way to turn it OFF. However, I once applied a soldering iron to a 3-terminal voltage regulator and then went to answer the phone. When I came back the next day, I discovered that the TO-3 package was still quite hot—300°C, which is normally recommended for only 10 seconds. When I cooled it off, the regulator ran fine and met spec. So, the old dictum that high temperature will necessarily degrade reliability is not always true. Still, it's a good practice not to get your power transistors that hot and to have a base drive that can pull the base OFF if they do.



***When using high-power amplifiers,*** *there are certain problems you just never have if you use an extremely large heat sink. This heat sink's thermal resistance is lower than 0.5°C/W.*

You can also run into problems if you tighten the screws on the heat sink too tight or if the heat sink under the device is warped or has bumps or burrs or foreign matter on it. If you tighten the bolt too much, you'll overstress and warp the tab and die attach. Overstress may cause the die to pop right off the tab. The insulating washer under the power transistor can crack due to overstress or may fail after days or weeks or months. Even if you don't have an insulating washer, overtorqueing the bolts of plastic-packaged power

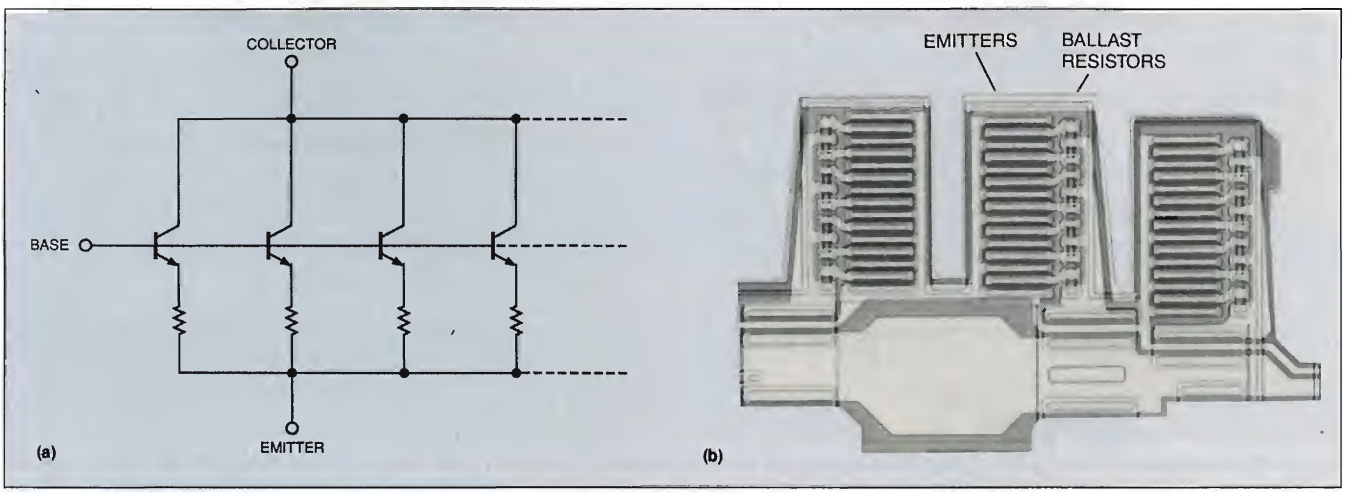



***Fig 1—Ballast resistors, also known as sharing resistors,*** *are often connected to the emitters of a number of parallelled transistors* ***(a)*** *to help the transistors share current and power. In an integrated circuit* ***(b)****, the ballast resistors are often integrated with adjacent emitters. (Photo of National Semiconductor Corp's LM138)*

*Mind your Ps and Qs and your Ps and Ns; don't mistakenly insert a pnp transistor in place of an npn, or vice versa.*

transistors is one of the standard ways to mistreat and kill these devices. Why does the number 10 inch-pounds max, 5 typ, stick in my head? Because that's the spec the Thermalloy man gave me for the mounting bolts of TO-220 packages.

### Apply the 5-second rule

Your finger is a pretty good heat detector—just be careful not to burn it with high voltages or very hot devices. A good rule of thumb is the 5-second rule: If you can hold your finger on a hot device for five seconds, the heat sink is about right, and the case temperature is about 85°C. If a component is too hot to touch, dot your finger with saliva and apply it to the hot object for just a fraction of a second. If the moisture dries up quickly, the case is probably around 100°C; if it sizzles instantaneously, the case may be as hot as 140°C. Alternatively, you can buy an infrared imaging detector for thousands of dollars, and you won't burn your fingers.

### Fabrication structures make a difference

Another thing you should know when using bipolar power devices is that there are two major fabrication structures: the epitaxial base and the single diffused **(Fig 2)** **(Ref 4)**. Transistors fabricated with the single-diffused structure are more rugged and have a wide safe-operating area. Epitaxial-base devices feature faster switching speeds but aren't as rugged as the single-diffused types. A good way to compare the two types is to look at the data sheets for the Motorola 2N3771 and MJ3771. The MJ3771 epi-base device has a current-gain bandwidth 10 times greater than the 2N3771 single-diffused device. The MJ3771 also has a switching speed faster than the 2N3771 when used as a saturated switch, but the 2N3771 has a considerably larger safe area if used for switching inductive loads. You can select which of these characteristics you prefer and order the part according to the specific number.

But there isn't always a clear correlation between the part number and its fabrication structure. For example, the popular 2N3055 is available in both epi-base and single-diffused versions. Since both versions meet and exceed the JEDEC specs, you could end up with either type. If you breadboard with one type and then start building in production with the other, you might suddenly find that the bandwidth of the device has changed by a factor of 10 or that the safe area doesn't match that of the prototypes.

Fortunately, there are ways to order the 2N3055 you want. If you want to buy an ordinary 2N3055—one that meets but does not exceed the device's JEDEC specs—the die will be about 90 mils on a side, the bandwidth will be about 2 MHz, and it will have a nominal safe area because it is an epi-base device. If you want to buy a really gutsy 2N3055, order a 2N3055H from RCA or SGS-Thomson. RCA calls the device's construction hometaxial, which is similar to single diffused. The part's die is about 180 mils on the side, so—obviously—the 2N3055H costs more than the

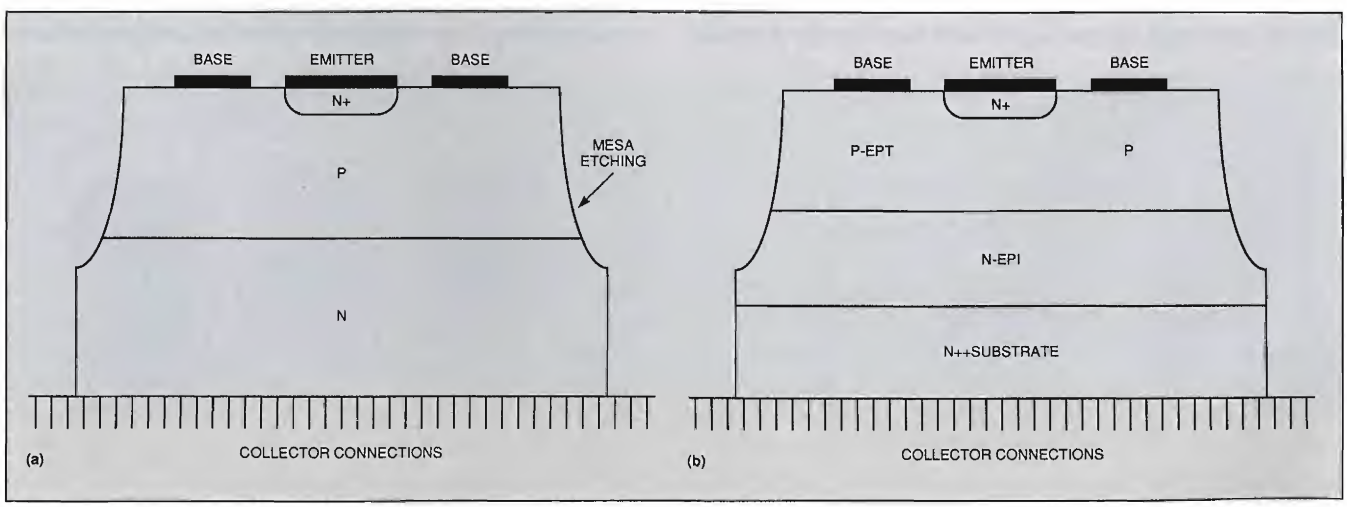



***Fig 2—The characteristics of power transistors*** *depend on their fabrication structure. In the single-diffused structure* ***(a)****, n-type dopants are diffused simultaneously into the front and back of a thin p-type wafer. This structure produces rugged transistors with wide safe operating areas. The more modern epitaxial-base transistor* ***(b)*** *takes advantage of the properties of several different epitaxial layers to achieve higher beta, faster speed, lower saturation, smaller die size, and thus, lower cost. Both structures involve mesa etching, which accounts for the slopes at the die edges.*

*Transistors require protection against excessive forward and reverse base current and electrostatic discharge.*

2N3055. The 2N3055H's bandwidth is only 0.3 MHz, but its safe area is considerably bigger than that of the ordinary 2N3055. Thus, 2N3055Hs are recommended for switching inductive loads.

Be careful not to confuse these epitaxial or single-diffused devices with planar power devices, such as the 2N5039 (**Fig 3**). The 2N5039 has a frequency response around 60 MHz but a considerably smaller safe area than those of the epitaxial and single-diffused devices. As with smaller transistors, such as the 2N2222 and 2N3904, planar devices tend to oscillate at high frequencies. The judicious use of ferrite beads in their emitter or base leads is often required for stable linear operation.

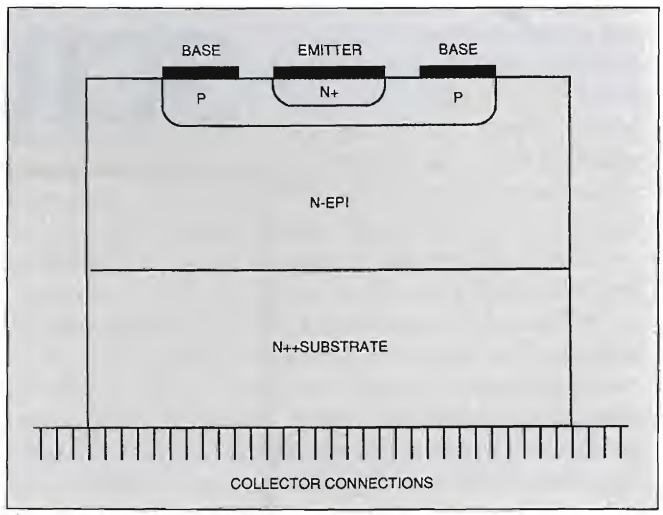



***Fig 3—Planar power transistors can achieve very small geometries,*** *small base-widths, and high frequency responses, but they're less rugged than the single-diffused and epitaxial-base types.*

### Power-circuit design requires expertise

For many power circuits, your transistor choice may not be as clear-cut as in the previous examples. So, be careful. Design in this area is not for the hotshot just out of school—there are many tricky problems that can challenge even the most experienced designers. For example, if you try to add small ballasting resistors to ensure current sharing between several transistors, you may still have to do some transistor matching. This matching isn't easy. You'll need to consider your operating conditions; decide what parameters, such as beta and $V_{be}$, you'll match; and figure out how to match different manufacturers' devices. Such design questions are not trivial.

When the performance or reliability of a power circuit is poor, it's probably not the fault of a bad transistor. Instead, it's quite possibly the fault of a bad or marginal driver circuit or an inadequate heat sink. Perhaps a device with different characteristics was inadvertently substituted in place of the intended device. Or perhaps you chose the wrong transistor for the application.

A possible scenario goes something like this. You build 10 prototypes, and they seem to work okay. You build 100 more, and half of them don't work. You ask me for advice. I ask, "Did they ever work right?" And you reply, "Yes." But wait a minute. There were 10 prototypes that worked, but the circuit design may have been a marginal one. Maybe the prototypes didn't really work all that well. If they're still around, it would be useful to go back and see if they had any margin to spare. If the 10 prototypes had a gain of 22,000, but the current crop of circuits has gains of 18,000 and fails the minimum spec of 20,000, your design is not really a failure. It's not that the circuit isn't working at all, it's just that your expectations were unrealistic.

After all, every engineer has seen circuits that had no right to work but did work—for a while. And then when they began to fail, it was obviously just a hopeless case. So, which will burn you quickest, a marginal design or marginal components? That's impossible to say. If you build in some safety margin, you may survive some of each. But you can't design with big margins to cover every possibility, or your design will become a monster.

### MOSFETs avoid secondary breakdown

When it comes to power transistors, MOSFETs have certain advantages. For many years, MOSFETs have been available that switch faster than bipolar transistors with smaller drive requirements. And MOSFETs are inherently stable against secondary breakdown and current hogging because the temperature coefficient of $I_{ds}$ vs $V_{gs}$ is inherently stable at high current densities. If one area of the power device gets too hot, it tends to carry less current and thus has an inherent mechanism to avoid running away. This self-ballasting characteristic is a major reason for the popularity of MOSFETs over bipolar transistors. However, recent criticism points out that when you run a MOSFET at high enough voltages and low current, the current density gets very small, the temperature coefficient of $I_{ds}$ vs $V_{gs}$ reverses, and the device's inherent freedom from current hogging may be lost (**Ref 5**). So at high volt-

*Don't be too quick to blame circuit problems on a transistor; the designer may have made some sloppy assumptions or had false performance expectations.*

ages and low current densities, watch out for this possibility.

The newer power MOSFETs are considerably more reliable and less expensive than the older devices. Even though you may need a lot of milliamps to turn the gate ON or OFF quickly, you don't need a lot of amps to hold it ON like you do with a bipolar transistor. You can turn the newer devices OFF quicker, too, if you have enough transient gate drive current available.

However, MOSFETs are not without their trouble spots. If you dissipate too many watts into a MOSFET, you can melt it just as you can melt a bipolar device. If you don't overheat a MOSFET, the easiest way to cause a problem is to forget to insert a few dozen or hundred ohms of resistance or a ferrite bead right at the gate lead of the device. Otherwise, these devices have such high bandwidths that they can oscillate at much higher frequencies than bipolar transistors.

For example, the first high-fidelity, all-MOSFET audio amplifier I ever saw blew up. It worked okay in the lab, but some misguided engineer decided that if a bandwidth of 5 Hz to 50 kHz was good, then 0.5 Hz to 500 kHz was better. Consequently, when the speaker cables were extended from 10 feet to 20 feet for a demonstration, the amplifier broke into a megahertz-region scream and promptly went up in smoke because of the lack of damping at the sources. I was told that after a minor redesign the amplifier was perfectly reliable. The redesign involved cutting the bandwidth down to a reasonable level, adding some ballasting in the sources, and tying antisnivet resistors directly to the gate pins. (Note: A snivet is a nasty, high-frequency oscillation originally found in vacuum-tube TV sets.)

As with bipolar transistors, MOSFETs are very reliable if you don't exceed their voltage, current, or temperature ratings. Dissatisfaction with a device's reliability or performance usually stems from the drivers or the related circuitry. Most MOSFETs have a maximum $V_{gs}$ rating of just 20 or 25V. A MOSFET may temporarily survive operation with 30 or 50V on the gate, but it's not safe to run it up there forever. If you apply excessive gate voltage, gradual gain or threshold degradation may occur. So—please—don't. Also, power MOSFETs are not quite as rugged as bipolars when it comes to surviving ESD transients. A common precaution is to add a little decoupling, clamping, or current-limiting circuitry, so that terminals accessible to the outside world can withstand ESD.

DMOS FETs are so easy to apply that we usually forget about the parasitic bipolar transistor that lurks in parallel with them. If [dV/dt] is too large at the drain, the drain junction is avalanched at too high a current and voltage, or the transistor gets too hot, the bipolar device turns ON and dies an instant death due to current hogging or an excursion from its safe operating area.

But I'm spoiled rotten. I'm accustomed to linear ICs, which have protection transistors built right in, so most of the transistor troubles are left to the IC designer. Discrete designs are appropriate and cost-effective for many applications, but the availability of linear ICs—especially op amps—eases your design task considerably. Next time, we'll discuss the ins and outs and innards of op amps. EDN

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## Author's biography

*For information about Bob Pease, see the* ***box****, "Who is Bob Pease, anyway?" on page 148 of the January 5, 1989, edition of EDN.*

**Article Interest Quotient (Circle One)**
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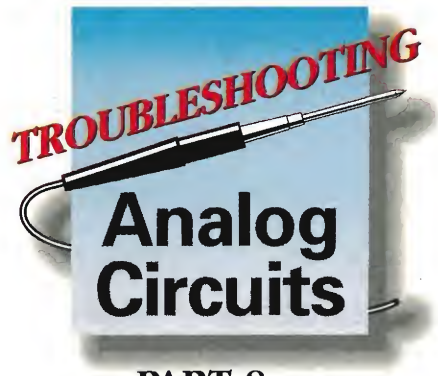



PART 8

# Keep a broad outlook when troubleshooting op-amp circuits

*External components often determine an op amp's performance—that's why Bob spent the previous seven parts of this series discussing them. But op amps aren't trouble-free: Oscillations and noise are two common problems. You'll have similar trouble with buffers and comparators, which Bob will discuss in part nine.*

Robert A Pease, *National Semiconductor Corp*

After many pages of fiddling around with many different components, we finally arrive at the operational amplifier itself. And the good news is that half of our problems are already solved. Why? Because it's the components around op amps that cause many of their problems. After all, the op amp is popular because external components define its gain and transfer characteristics.

So, if an amplifier's gain is wrong, you quickly learn that you should check the resistor tolerances, not the op amp. If you have an ac amplifier or filter or integrator whose response is wrong, you check the capacitor, not the op amp. If you see an oscillation, you check to see if there's an oscillation on the power-supply bus or an excessive amount of phase shift in the feedback circuit. If the step response looks lousy, you check your scope or your probes or your signal generator because they're as likely to have gone flaky as the op amp is. These failures are the reason we studied so many passive components: The over-all performance of your circuit is often determined by those passive components. And yet, there are exceptions. There *are* quite a few ways an op amp itself can goof up.

## Don't sweat the small stuff

Before we discuss serious problems, however, you should be aware of the kinds of op-amp errors that aren't significant. First of all, it generally isn't reasonable to expect an op amp to be linear, nor is its nonlinearity all that significant. For example, what if an op amp's gain is 600,000 for positive signals but 900,000 for negative signals? This mismatch of gain slope causes a nonlinearity of about 10 μV in a 20V p-p unity-gain inverter. Heck, the voltage coefficients and temperature-coefficient errors of the feedback resistors will cause a lot more error than that! Even the best film resistors have a voltage coefficient of 0.1 ppm/V, which will cause more nonlinearity than this gain error.

Similarly, an op amp may have an offset-voltage temperature-coefficient specification of 1 μV/°C, but the op amp's drift may actually be 0.33 μV/°C at some temperatures and 1.2 μV/°C at others. Twenty or thirty years ago, battles and wars were fought over this kind of specsmanship, but these days, most engineers agree that you don't need to sweat the small stuff. Most applications don't require an offset drift less than 0.99 μV for each and every degree. Most cases are quite happy when a 1 μV/°C op amp drifts less than 50 μV over 50 degrees.

*When it comes to op amps, don't sweat the small stuff.*

Also, you don't often need to worry about bias current and its temperature coefficient or the gain error. If the errors are well behaved and fit inside a small box, well, that's a pretty good part.

A good example of misconstrued specs is the common-mode error. We often speak of an op amp as having a CMRR of 100 dB. Does this number mean that the common-mode error is exactly one part in 100,000 and has a nice linear error of 10 μV per volt? Well, this performance is possible, but not likely. It's more likely that the offset-voltage error as a function of common-mode voltage is nonlinear (**Fig 1**).

It really bugs me when people say, "The op amp has a common-mode gain, $A_{VC}$, and a differential gain, $A_{VD}$, and the CMRR is the ratio of the two." This statement is silly business. It's NOT reasonable to say that the op amp has a differential gain or common-mode gain that can be represented by a single number. Neither of these gain numbers could ever be observed or measured with any precision or repeatability. Avoid the absurdity of trying to measure a "common-mode gain of zero" to compute that your CMRR slope is infinity. You'll get more meaningful results if you just measure the change in offset voltage, $V_{OS}$, as a function of common-mode voltage, $V_{CM}$, and observe the nonlinear parts of the curve. What's a good way to measure the change in $V_{OS}$ versus $V_{CM}$—the CMRR—of an op amp? I know of two test circuits that work pretty well—send me your request and I'll mail you a copy. But watch out for tests that add the common-mode error and the gain error because the gain error normally overshadows the common-mode error.

Some data sheets include a CMRR-versus-frequency curve that looks the same as the gain-bandwidth-product curve, which is normally the sign of a foolish measurement error. Yes, in 1989 you can still see this kind of ridiculous curve in the data sheets of various manufacturers. The LF401's data sheet is one example, but this situation is being fixed. In most cases, you can expect an op amp's CMRR at 1 kHz to be much better than its gain at 1 kHz. If the data sheet says they're the same, then it's probably wrong.

**Measure bias current rather than impedance**

Another op-amp spec you don't need to worry about is the differential input impedance. Every year I still get asked, "How do we measure the input impedance of an op amp?" And every year I trot out the same answer: "We don't." Instead, we measure the bias current. There's a close correlation between the bias current and the input inpedance, so if the bias current is low, the input impedance (differential and common-mode) must be high. So, let's not even think about how to measure input impedance because I haven't measured it in the last five years.

Generally, an ordinary differential bipolar stage has a differential input impedance of $1/(20 \times I_B)$, where $I_B$ is the bias current. But this number varies if the op amp includes emitter-degeneration resistors or internal bias-compensation circuitry. You can easily test the common-mode input resistance by measuring $\Delta I_B$ versus $V_{CM}$.

I've measured some input capacitances and find the circuits of **Fig 2** to be quite useful. Input-capacitance

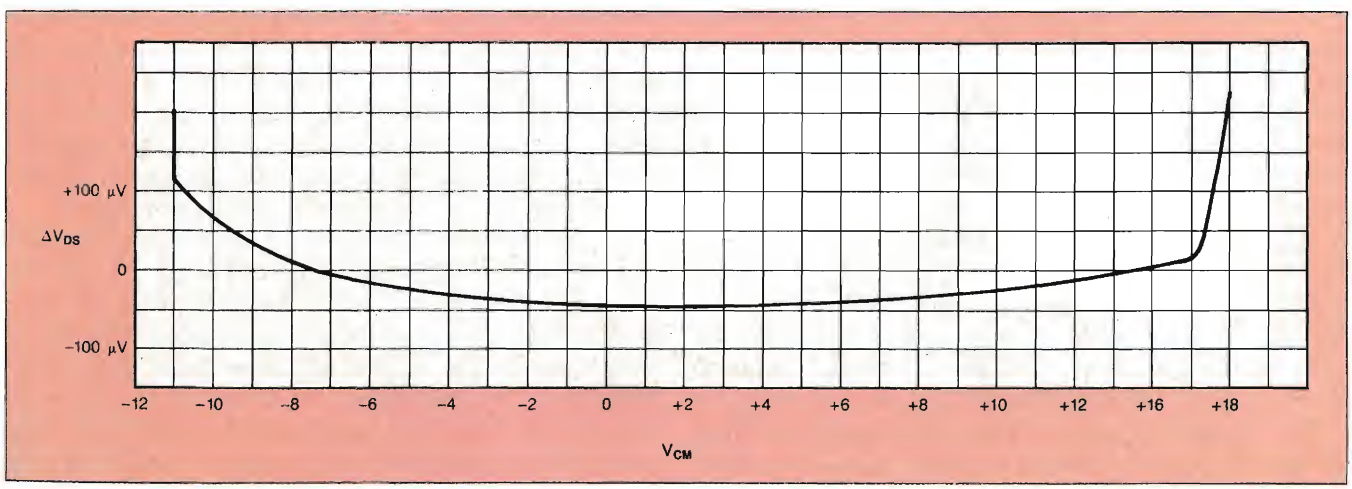



***Fig 1—The CMRR of an op amp can't be represented** by a single number. It makes more sense to look at the CMRR curve, $\Delta V_{OS}$ vs $V_{CM}$, and note its nonlinearities.*

data is normally of interest only for high-impedance high-speed buffers or for filters where you want to make sure that the second-source device has the same capacitance as the op amps that are already working okay.

### Recognize false "error" characteristics

Sometimes, an op amp may exhibit an "error" that looks like a bad problem, but isn't. For example, if an op-amp output is ramping at 0.3V/μsec, you might be surprised when you discover that the inverting input, a summing point, is NOT at ground. Instead, it may be 15 or 30 or 100 mV away from ground. Why isn't the inverting input at the "virtual ground" that the books teach us? The virtual ground theory is applicable at dc and low frequencies, but if the output is moving at a fast speed, then expecting the summing point to be exactly at ground is unreasonable. In this example, $dV_{OUT}/dt$ equals $2\pi V_{IN}$ times the unity-gain frequency. So, 15 mV of $V_{IN}$ is quite reasonable for a medium-bandwidth op amp, such as an LF356, and 50 or 70 mV is quite reasonable for a μA741. If you want an op amp to move its output at any significant speed, there has to be a significant error voltage across the inputs for at least a short time.

Also beware of op-amp models and what they might mistakenly tell you. For instance, the "standard" equation for a single-pole op amp's gain is $A = A_0(1/1 + j\omega T_0)$. This equation implies that when the dc gain, $A_0$, changes, the high-frequency gain, A, changes likewise. Wrong! With the growing popularity of computer modeling, I have to explain this to a would-be analyst every

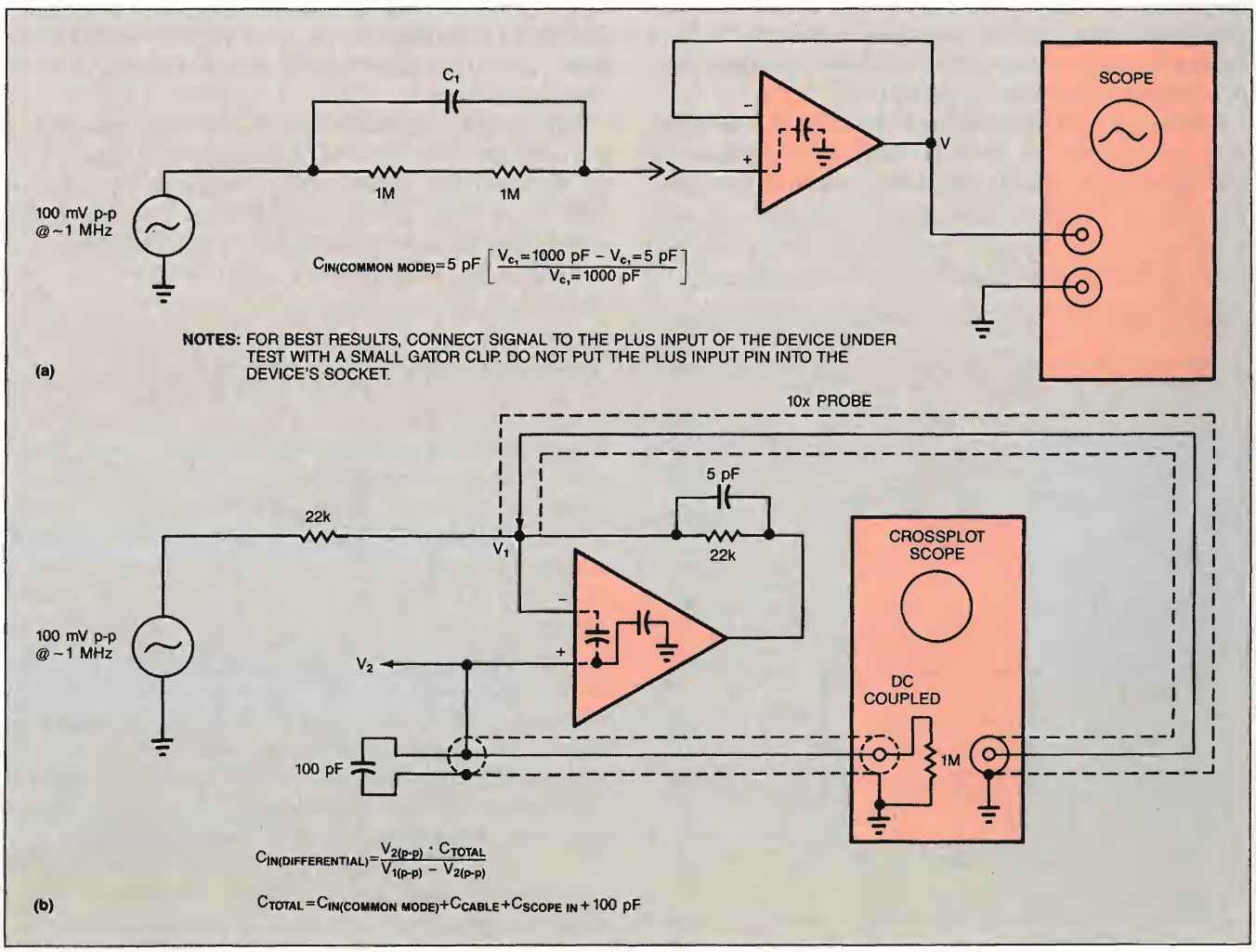



***Fig 2—These circuits let you test*** *an op amp's common-mode input capacitance* ***(a)*** *and differential input capacitance* ***(b)***.

*Don't expect the textbook "virtual-ground theory" to apply at high frequencies; for the output to slew rapidly, there must be an error voltage between the inputs.*

month. NO, there is almost no correlation between the high-frequency response and the spread of dc gain. There are several ways to get an op amp's dc gain to change: Change the temperature, add on or lift off a load resistor, or swap in an amplifier with higher or lower dc gain. Although the dc gain can vary several octaves in any one of these cases, the gain-bandwidth product stays about the same. If there ever were any op amps whose responses *did* vary with the dc gain, they were abandoned many years ago as unacceptable.

So, your op-amp model is fine if it gives you a fixed gain-bandwidth product. But if the gain at 1 MHz doubles every time you double the dc voltage by reducing the load, you're headed for trouble and confusion. I once read an op-amp book that stated that when the dc gain changed, the first pole remained at the same frequency. In other words, the author claimed that the gain-bandwidth product increased with the dc gain. Wrong. I wrote to the author to object and to correct, but I never heard back from him.

I often see op-amp spec sheets in which the open-loop output impedance is listed as 50Ω. But by inspecting the gain specs at two different load-resistor values, you can see that the dc gain falls by a factor of 2 when a load of 1 kΩ is applied. Well, if you have an op amp with an output impedance of 1 kΩ, its gain will fall by a factor of 2 when you apply a 1-kΩ load. But if its output impedance were 50Ω, as the spec sheet claimed, it would only fall 5%. So, whether it's a computer model or a real amplifier, be suspicious of output impedances that are unrealistically low.

### Watch out for real trouble

What real trouble can an op amp get you into without much help from the components? Well, you could have a part with a bad $V_{OS}$. Or if the temperature is changing, the thermocouples of the op amp's Kovar leads may cause small voltages differences between the op-amp leads and the copper of the pc board. Such differences can amount to 1/10 or 1/20 of a Celsius degree times 35 μV per degree, which equals 2 to 3 μV. A good way to avoid this problem is to put a little box over the amplifier to keep breezes and sunshine off the part. That's very helpful unless it's a high-power op amp. Then just repeat after me, "Heat is the enemy of precision," because it is.

You should remember, too, that not all op amps of any one type have the exact same output-voltage swing or current drive or frequency response. I get phone calls every four or five weeks from customers who complain, "We have a new batch of your op amps, and they don't have as good an output swing (or output

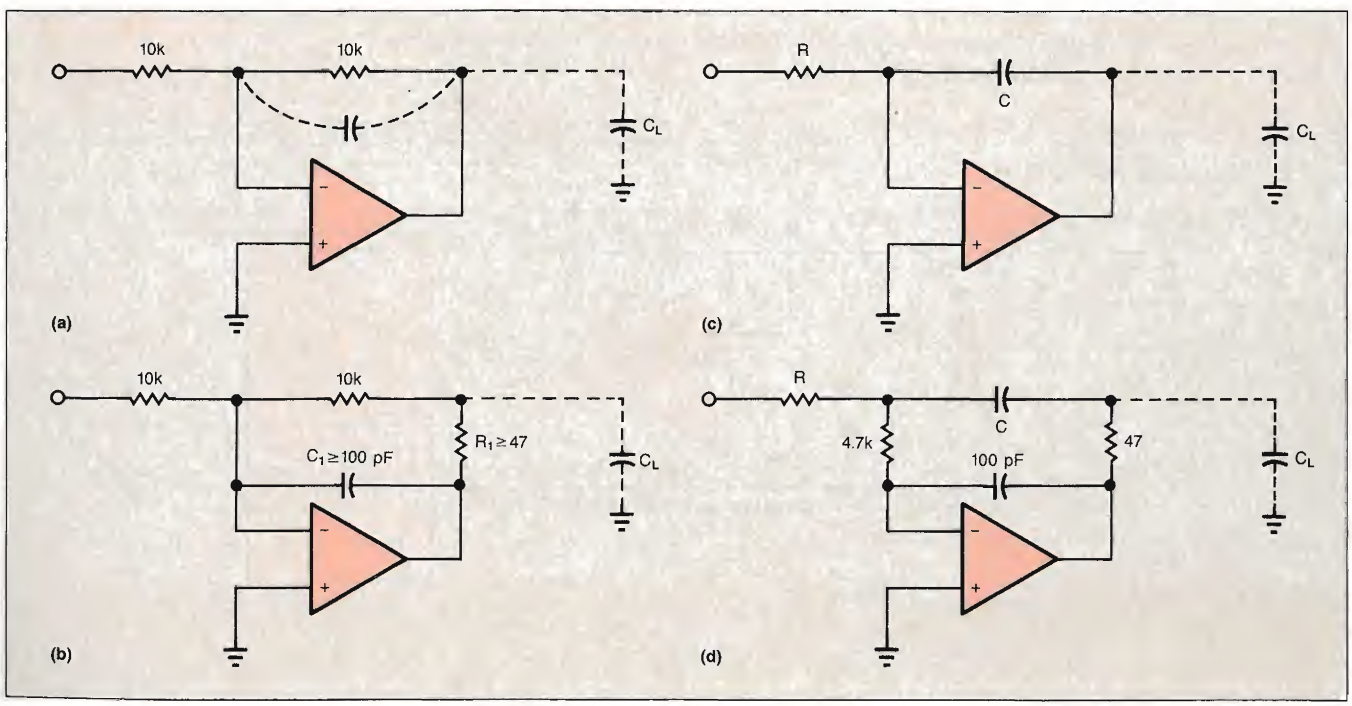



***Fig 3—You can easily modify** the basic inverter **(a)** and integrator **(c)** to decouple capacitive loads **(b** and **d)**.*

current or frequency response) as the previous batches." When I check it out, 98% of the time I find that a part with extremely good performance is just a random variation. The customer was in the habit of expecting the parts to be better than average. When they got some parts that were still much better than the guaranteed spec but worse than average or "typical," they found themselves in trouble. It's always painful to have to tell your friends that you love them when they trust you, but they really shouldn't trust your parts to always be better than average.

### Oscillations often accompany op amps

One of the most troublesome problems you can have with op amps is oscillation. You can build an oscillator out of any gain block, but any gain block can also oscillate when you don't want it to. Op amps are no exception. Fortunately, most op amps these days are well behaved, and you only need to take four basic precautions to avoid oscillations.

First, always use power-supply bypass capacitors on each supply and install them near the op amp. For high-frequency op amps, the bypass capacitors should be very close to the device for best results. In high-frequency designs, you often need ceramic and tantalum bypass capacitors. Using bypass capacitors isn't just a rule of thumb, but a matter of good engineering and optimization.

### Capacitive loads induce ringing

Second, avoid unnecessary capacitive loads; they can cause an op amp to develop additional phase shift, which causes the op amp to ring or oscillate. These effects are especially noticeable when you connect a 1x scope probe or add a coaxial cable or other shielded wire to an op amp to convey its output to another circuit. Such connections can add a lot of capacitance to the output. Unless you're able to prove that the op amp will be stable driving that load, you'd better add some stabilizing circuits. It doesn't take a lot of work to BANG the op amp with a square wave or a pulse and see if its output rings badly or not. You should check the op amp's response with both positive and negative output voltages because many op amps with pnp-follower outputs are less stable when $V_{OUT}$ is negative or the output is sinking current.

I've seen pages of analysis that claim to predict capacitive-loading effects, but they're a complete waste of time. The output impedance of an op amp is usually not purely resistive. And if the impedance is low at audio frequencies, it often starts to rise inductively at high frequencies, just when you need it low. Conversely, some op amps have a capacitive output characteristic, so when you add more capacitance on the output, the op amp just slows down a little and doesn't change its phase very much. But if an op amp is driving a remote, low-resistive load that has the same impedance as the cable, the terminated cable will be resistive at all frequencies and capacitive loading won't be a problem.

You can decouple an inverter's and integrator's capacitive load as shown in **Fig 3**. If you choose the components well, any op amp can drive any capacitive load from 100 pF to 100 μF. The dc and low-frequency gain is perfectly controlled, but when the load capacitor gets big, the op amp will slow down and eventually have trouble slewing the heavy load. Good starting-point component values are $R_1 = 47\Omega$ and $C_F = 100$ pF. These values usually work well for capacitive loads from 100 pF to 20,000 pF. If you have to make an integrator or a follower, you'll need an additional 4.7-kΩ resistor as indicated in **Fig 3**.

In some cases, as with an LM110 voltage follower,

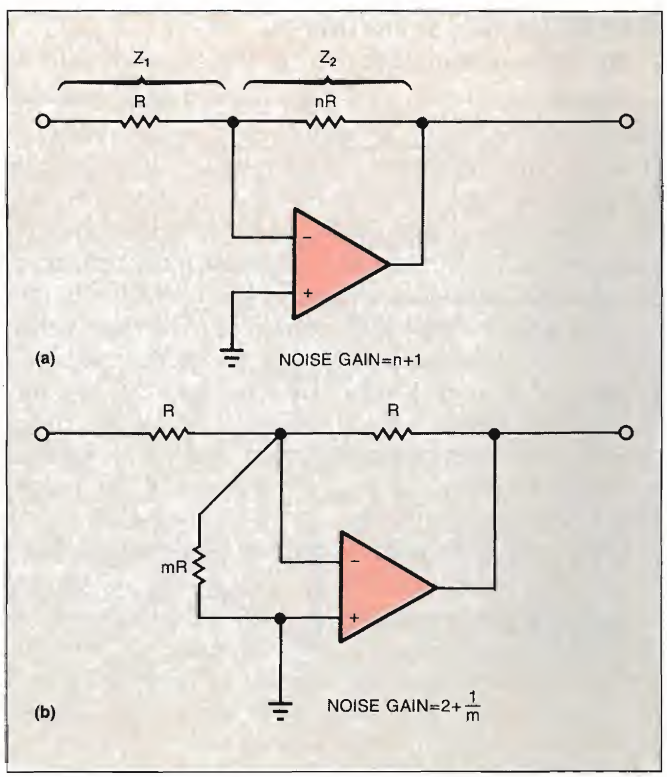



***Fig 4—By adding just a single resistor,*** *you can tailor the noise gain of a standard inverter.*

*Any gain block can oscillate, even when you don't want it to—op amps are no exception.*

the feedback path from the output to the inverting input is internally connected and thus unavailable for tailoring. In this case, we can pull another trick out of our bag: the tailoring of noise gain. Noise gain is defined as $1/\beta$, where $\beta$ is the attenuation of an op amp's feedback network. For instance, the $\beta$ of the standard inverter configuration (**Fig 4a**) equals $Z_1/(Z_1+Z_2)$, so the noise gain equals $N+1$. You can raise the noise gain as shown in **Fig 4b**.

If you're using a low-noise-gain op-amp configuration, such as a unity-gain follower that has a noise gain of 1 (**Fig 5a**), it's obvious that for stability the op amp can't have appreciable phase shift out near its unity-gain frequency. If you can increase the noise gain to 4 or 5, the requirement for low phase shift eases considerably. No, you don't have to change the signal gain to 5. A noise gain of 5 or greater is easy to achieve (**Fig 5b**) while maintaining a gain of 1 for the signal. Even the unity-gain follower with a wire from the output to the inverting input can be saved, as illustrated in **Figs 5c** and **d**. You'll find a more complete description of these circuits in **Ref 1**. I should also mention that these concepts were used by Glenn DeMichele in his EDN Design Idea for which he won the 1988 Design Idea award (**Ref 2**).

My third recommendation to prevent oscillation in general-purpose op amps is to add a feedback capacitor across $R_F$ unless you can show that this capacitor isn't necessary. This capacitor's function is to prevent phase lag in the feedback path. Of course there are exceptions, such as the LF357 or LM349, which are stable at gains or noise gains greater than 10. Adding a feedback capacitor across the feedback paths of these op amps would be exactly the wrong thing to do.

Recently I observed that a number of National Semiconductor op-amp data sheets were advising feedback capacitor values of

$$C_F = \frac{C_{IN}R_{IN}}{R_F}.$$

But, if you had an ordinary op amp whose $C_{IN}$ was 5 pF and an inverter with a gain of $-0.1$, this equation would tell you to use a $C_F$ of 50 pF and accept a frequency response of 3 kHz. That would be absurd. If you actually build this circuit, you'll find that it works well with $C_F = 1.5$ pF, which gives the inverter a bandwidth of 100 kHz. So, we at NSC have just agreed to deep six that equation. We have a couple new formulas, which we've checked carefully, and we have found that you can get considerably improved bandwidth and excellent stability. For high values of

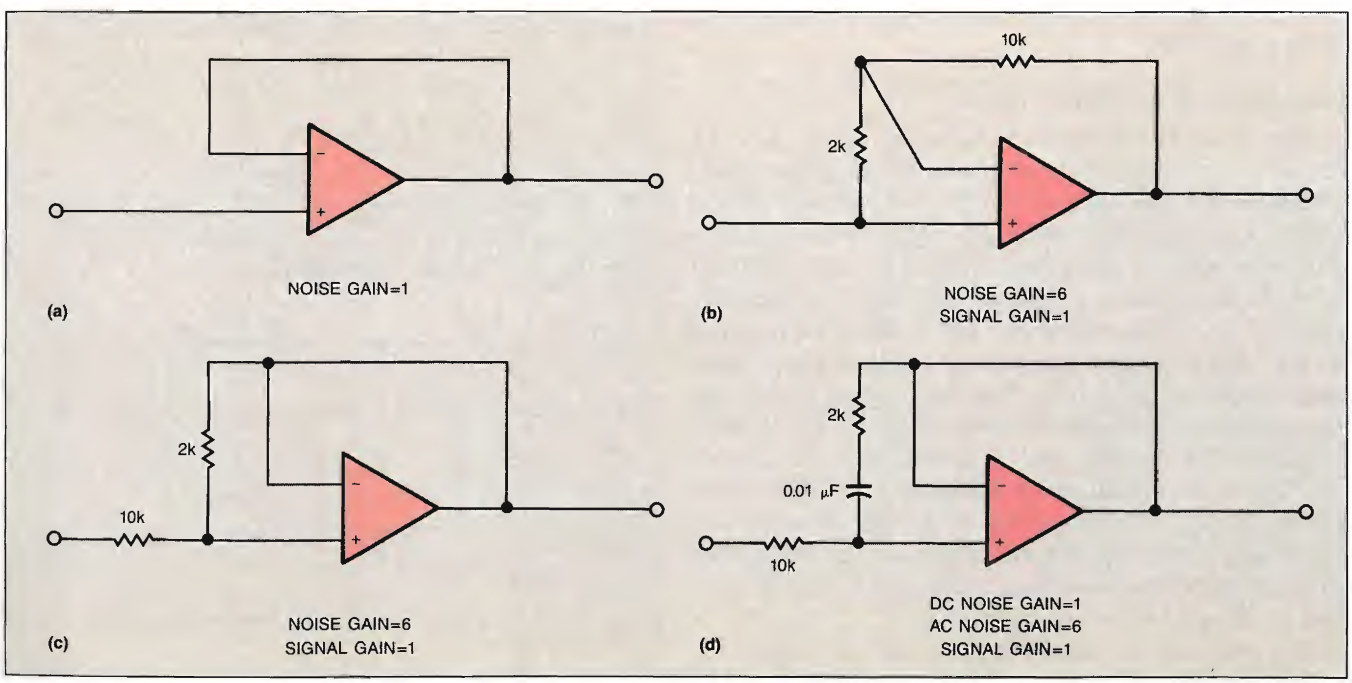



***Fig 5—By manipulating the noise gain of an amplifier,*** *you can stabilize unity-gain followers while maintaining the desired closed-loop gain.*

gain and $R_F$, use the following equation:

$$C_F = \sqrt{\frac{C_{IN}}{GBW \times R_F}},$$

where GBW is the gain-bandwidth product. In those cases in which the gain or impedance is low, such as where

$$(1 + R_F/R_{IN}) \leq 2\sqrt{GBW \times R_F \times C_{IN}},$$

use the following equation:

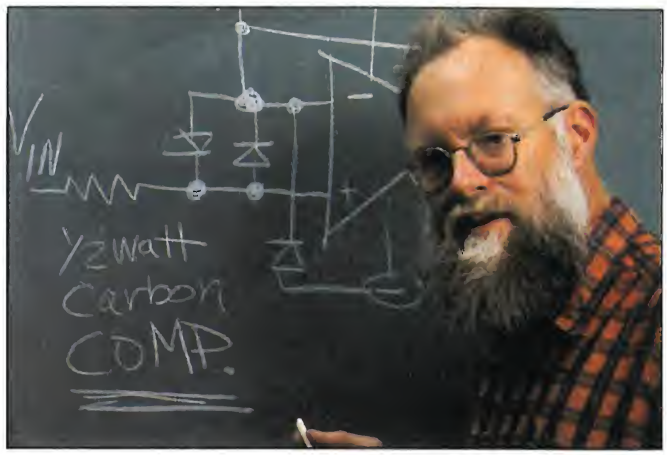
$$C_F = \frac{C_{IN}}{2 + 2\,R_F/R_{IN}}.$$

I won't bore you with the math, but these equations did come from real analytical approaches that have been around for 20 years—I championed them back at Philbrick Researches. The value of $C_F$ that you compute is not that critical, it's just a starting point. You really must build and trim and test the circuit for overshoot, ringing, and freedom from oscillation. If the equation said 1 pF and you get a clean response only with 10 pF, you'd be suspicious of the formula. Note that when you go from a breadboard to a pc board, the stray capacitances can change, so you must recheck the value of $C_F$. In some cases, you may not need a separate capacitor if you build 0.5 pF into the board.

My last recommendation is that when you think the circuit is okay—that is, free from oscillation—test it anyway per Pease's Principle (see **box**) to make sure it's as fast or stable as you expect. Be sure that your circuit isn't ringing or oscillating at any expected operating condition or load or bias.

In addition to oscillatory behavior, another problem you might have when using op amps is noise. Most op amps have fairly predictable noise. It's often right down at theoretical levels, especially at audio frequencies. There's a pretty good treatment of noise and its effects in various applications in Thomas Frederiksen's book (**Ref 3**). Also, if you want to optimize the noise for any given source resistance or impedance, National Semiconductor's Linear Applications Note AN222 (**Ref 4**) has some good advice as does the article in **Ref 5**.

You'll have difficulty with noise when it's unpredictable or when op amps of a particular type have varying noise characteristics. This problem rarely happens at audio frequencies but is likely to happen sporadically at low frequencies, such as 10 or 100 Hz or even lower




Photographs by Peggi Willis

***External components determine an op amp's operation,*** *and you can often keep a circuit out of trouble only by using components with characteristics that aren't found in books or data sheets.*

frequencies. Every manufacturer of transistors and amplifiers tries to keep the noise low, but occasionally some noisy parts are built. Sometimes the manufacturer is able to add tests that screen out the noisy parts. But these tests aren't cheap if they take even one second of tester time, which may cost three cents or more.

### Beware of popcorn noise

Flicker noise, also known as 1/f noise, is ac noise that exists at low frequencies. And even more insidious than 1/f noise is popcorn noise—a type of electrical noise in which bursts of square steps are added to the normal thermal noise at random times. Popcorn noise occurs rarely these days; but, unfortunately, it's not at 0%, not even with the cleanest processing and the best manufacturers. I've been chastised and told that some of my amplifiers are noisy compared with those of certain competitors. But when I look at the competitor's data and plots, I see 1/f and popcorn noise lurking unnoticed in a corner. On high-performance parts, we try to screen out the noisy ones. But when a few parts have a spacing of two to 10 seconds between bursts of popcorn, it's not cost effective to look for those parts. Only a small percentage of our customers would want to reject that part AND pay for the testing. Remember, 10 seconds of testing time equals 30 cents; time equals money.

Although oscillation and noise problems may be the most common ones you'll encounter when you use op amps, there's a host of other characteristics that are helpful to look out for. These characteristics include

*To avoid oscillations, use bypass and feedback capacitors, avoid or compensate for heavy capacitive loads, and apply Pease's Principle.*

overload or short-circuit recovery, settling time, and thermal response. Many op amps have a fairly prompt recovery from overdrive when you make the output go into the stops—that is, when you force the output too close to the power-supply rails. For most op amps, this recovery characteristic is not defined or specified. One recently advertised op amp requires only 12 nsec to come out of the stops. Just about all other op amps are slower to one degree or another. The recovery time for chopper-stabilized amplifiers can be seconds.

Even if you have a fast op amp that doesn't have a delay coming out of limit, there may be circuits, such as integrators, that take a long time to recover if you overdrive the output and inputs. To avoid these cases, a feedback bound made of zeners and other diodes may be helpful (**Ref 6**). However, if you have a differential amplifier, you may not be able to use any zener diode feedback limiters. I recall the time I designed a detector circuit using a fast, dielectrically isolated op amp. When I went to put it into production, nothing worked right. It turned out that the manufacturer had just recently redesigned the chip to cut the die size by 50%. The new and improved layout slowed down the op amp's overdrive-recovery time. I wound up redesigning the circuit to use an LM709. I saved a lot of pennies in the long run, but the need to change parts didn't make me very happy at the time.

**Rely only on guaranteed specs**

Don't rely on characteristics that aren't specified or guaranteed by the manufacturer. It's perfectly possible for you to test a set of samples and find that they feature some desired performance characteristic that is not specified by the manufacturer. But if the next batch doesn't fulfill your requirements, whom are you going to get angry at? Don't get mad at me, because I'm warning you now. Any unspecified conditions may cause a test result to vary considerably compared to a guaranteed tested specification. If you have to work in an unspecified range, you should keep a store of tested good ICs in a safe as insurance. If a new batch comes in and tests "bad" you'll have some backup devices.

I recall a complaint from a user of LM3046 transistor

## Pease's Principle

For many years, I've been cautioning people: If you have a regulator or an amplifier circuit and it oscillates, DO NOT just add resistors or capacitors until the oscillation stops. If you do, the oscillation may go away for a while, but after it lulls you into complacency, it will come back like the proverbial alligator and chomp on your ankle and cause you a great deal of misery.

Instead, when you think you have designed and installed a good fix for the oscillation, BANG on the output with square waves of various amplitudes, frequencies, and amounts of load current. One of the easiest ways to perform this test is to connect a square-wave generator to your circuit through a couple hundred ohms in series with a 0.2-μF ceramic disc capacitor. Connect the generator to the scope, so you can trigger on the square-wave signal. Also, apply an adjustable dc load that's capable of exercising the device's output over its full-rated output-current range or, in the case of an op amp, over its entire rated range for output voltage AND current.

To test an op amp, try various capacitive loads to make sure it can drive the worst case you expect it to encounter. For some emitter-follower output stages, the worst case may be around 10 to 50 pF. The oscillation may disappear with heavier capacitive loads.

When you BANG a device's output and that output rings with a high Q, you know your "fix" doesn't have much margin. When the output just goes "flump" and doesn't even ring or overshoot appreciably, you know your damping is effective and has a large safety margin. Good! Now, take a hair dryer and get the circuit good and warm. Make sure that the damping is still pretty well behaved and that the output doesn't begin to sing when you heat the capacitor or power transistor or control IC or ANYTHING.

I don't mean to imply that you shouldn't do a full analysis of ac-loop stability. But the approach I have outlined here can give you pretty good confidence in about five minutes that your circuit will (or won't) pass a full set of exhaustive tests.

*To get the most out of the time you spend troubleshooting, thoroughly understand a problem before squashing it and moving on to the next.*

arrays: A fraction of the parts failed to log accurately over a wide range. The "bad" ones turned out to have a beta of 20 at a collector current of 50 pA, versus a beta of 100 for the "good" ones. I convinced the user that keeping a few hundred of these inexpensive parts in a safe (yes, literally) would be a lot cheaper than getting the manufacturer to sort out high-β devices.

Op amps and other linear ICs can also have errors due to thermal tails. These tails occur when the change of heat in one output transistor causes a thermal gradient to sweep across the chip. This change occurs gradually, often over milliseconds, and causes uneven heating of input transistors or other sensitive circuits. Many high-power circuits and precision circuits, such as the LM137, are tested these days for thermally caused error. These tests aren't performed just on power ICs, but also on precision references and instrument-grade op amps. In fact, a recent article by a Tektronix engineer **(Ref 8)** points out that thermal tails can be a major source of error in fast signal amplifiers and that innovative circuit design can minimize those overdrive-recovery errors.

These days, just about every manufacturer's monolithic op amps will survive a short from the output to ground. (Hybrids are often unprotected.) But it's not always clear whether an op amp will survive a short circuit to the positive or negative supply or, if so, for how long. You may have to ask the manufacturer, and you can expect some kind of negative answer. You'll be told to avoid overheating the device above its absolute maximum junction temperature. Even if an amplifier or regulator does recover fairly quickly from current limit, nobody will guarantee that it won't oscillate when in current limit. Nor will the manufacturer have much knowledge about how the circuit recovers from the thermal gradients caused by current limit. If an op amp survives a high-power overload, it's not fair to ask the device to recover its full accuracy very quickly. The most you really can ask for is that it survives with no degradation of reliability—that's the standard.

Some op amps, but mostly voltage regulators and other linear ICs, have an on-chip temperature limiter. Thermal shutdown circuits can improve reliability. If a heavy overload is applied for a long time, or there is no heat sink, or the ambient is just too hot, these circuits detect when the chip's temperature exceeds 150°C and then turn off the output. The thermal-limiter circuit in the LM117 and other early power ICs just decreased the output current to a safe dc value to hold the die temperature to around 160°C. In other cases, these thermal limiters oscillate On and Off with a duty cycle that ensures the 160°C chip temperature. As we at NSC were about to design the LM137, we looked back and decided the latter characteristic was preferable, so we designed about five degrees of thermal hysteresis into the thermal-limit circuit. That way, the circuit makes a strong attempt to restart its heavy load with a repetition rate of about 100 Hz.

***When you're trying to troubleshoot a one-of-a-kind circuit,*** *it helps if you can remember how the circuit is supposed to operate. A little bit of documentation and a schematic with some scribbled notes can save you a lot of grief.*

So, we actually designed an oscillation into this thermal-limit circuit, but we never bothered to mention it on the data sheet. H'mmm, we shouldn't be so sloppy. I apologize. I'll do better next time. (This situation has a bearing on one of my pet peeves: bad data sheets. I get really cross about bad ones, and I really do try hard and work hard to make good ones. Refer to "How to Read a Data Sheet" **(Ref 9)** because bad data sheets can get the user into trouble.)

### Different methods uncover different errors

Now that you know some op-amp problems to look out for, how do you actually troubleshoot an op-amp circuit? I usually split my plan along two lines: ac and dc problems. Examples of ac problems include oscillations and ringing; dc problems include bad errors and pegged outputs, which are outputs stuck at either the positive or negative supply rail. Obviously, you need a scope to be sure the circuit isn't oscillating. It always makes me nervous when I find out that the customer I'm trying to help DOESN'T EVEN HAVE A SCOPE. I can understand if an engineer only has a crummy

*If your design requires op amps that perform better than the guaranteed specs, keep a supply of "good parts" in a safe place for insurance.*

scope, but there are certain problems you cannot expect to solve—nor can you even verify a design—if you don't have a scope.

If the problem is an ac problem, I first make sure that the input signals are well behaved and at the values I expect them to be. Then I put my scope probes on all the pins and nodes of the circuit. Sometimes it's appropriate to use a 10x probe, and other times I shift to 1x mode. Sometimes I ac couple the scope; sometimes I dc couple it. I check all the pins, especially the power-supply pins. Then—depending on what clues I see—I poke around and gather symptoms by adding capacitors or RC boxes to assorted circuit nodes. I try to use two probes to see if the input and output have an interesting phase relationship, and I simultaneously verify that the output is still oscillating.

Many of the techniques I use depend on whether the circuit is one I've never tried before or one that I see all the time. Sometimes I find an unbelievable situation, and I make sure that I understand what's going on before I just squash the problem and proceed to the next. After all, if I'm fooling myself, I really ought to find out how or why so I won't do it again.

If the op amp exhibits a dc error or a peg, I first check with my scope to see that there's no oscillation. Then I bring in my 5-digit DVM and scribble down a voltage map on a copy of the schematic. On the first pass, I'm likely to just keep the numbers in my head to see if I can do a quick diagnosis of a problem that's obvious. Failing that, I start writing meticulous notes to help look for a more insidious problem. I look at the numbers on the schematic and try to guess the problem. What failure could cause that set of errors? A resistor of the wrong value? A short? An open? Then I try to cook up a test to confirm my theory. Sometimes I have to disconnect things, but I try to minimize that. Sometimes adding a resistor or voltage or current will yield the same result, and it's much easier than disconnecting components.

If an amplifier circuit isn't running at all, sometimes the right thing to do is to reach into the circuit and "grab" one amplifier's input and force it to go above and below the other input. If the output doesn't respond at all, you have a dead amplifier, an amplifier with no connections, or a stuck output. This open-loop test is not obvious, but its results are.

Many of these op-amp troubleshooting tips are applicable to other components as well. The next article in this troubleshooting series will continue with buffers, comparators, and related devices. EDN

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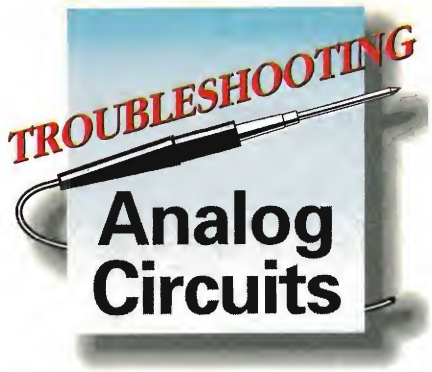
## Author's biography

*For information about Bob Pease, see the* ***box****, "Who is Bob Pease, anyway?" on page 148 of the January 5, 1989, edition of EDN.*

**Article Interest Quotient (Circle One)**
**High 491 Medium 492 Low 493**




PART 9

# Troubleshooting techniques quash spurious oscillations

*Oscillations are the ubiquitous bugaboos of analog-circuit design. Not only can you encounter oscillating op amps, as described in part 8, but also oscillating transistors, switching regulators, optoisolators, comparators, and buffers. And, if you think about it, latched-up circuits are just the opposite of oscillating ones, so Bob included them here, too.*

Robert A Pease, *National Semiconductor Corp*

Recall the corollary of Murphy's Law that states: "Oscillators won't. Amplifiers will."—oscillate, that is. The knack of spotting and quashing spurious oscillations is, for some fortunate people, a well-developed art. But others have not learned this art well.

I obviously cannot tell you how to solve every kind of oscillation problem. But, I will give you some general principles and then notes on what can go wrong with various components, including comparators and buffers. This information along with a few suggested procedures and recommended instruments will get you off to a good start.

Here are some of the types of oscillations that can pop up unexpectedly:

- Oscillations at very high frequencies—hundreds of megahertz—because of a single oscillating transistor
- Oscillations at dozens of megahertz arising from stray feedback around a comparator
- Oscillations at hundreds of kilohertz because of an improperly damped op-amp loop, an unhappy linear voltage-regulator IC, or inadequately bypassed power supplies
- Moderate-frequency oscillations of a switching-regulator loop because of improper loop damping
- Low-frequency oscillations coming from physical delays in electromechanical or thermal servo loops.

As these general descriptions indicate, the frequency of an oscillation is a good clue to its source. An electric-motor loop can't oscillate at 10 MHz, and a single transistor can't rattle at 100 Hz. So when an engineer complains of an oscillation, the first question I have is, "Oh, at what frequency?" Even though the frequency is often a good clue, engineers sometimes never even notice what the frequency was. This omission tends to make troubleshooting by phone a challenge.

At very high frequencies, 20 to 1000 MHz, the layout of a circuit greatly affects the possibility of oscillation. One troubleshooting technique is to slide your finger around the circuit and see if at any point an oscillation improves or worsens. Remember, knowing how to make an oscillation stronger is not worthless knowledge—that information can provide clues on how to make the oscillation weaker.

I remember being very impressed when a colleague showed me that some of the earliest IC amplifiers had a tendency to self-oscillate at 98 MHz with certain levels of output voltage. Putting a grid-dip oscillator nearby caused increases or decreases in the problem.

*At very high frequencies—20 MHz to 1000 MHz—the layout of a circuit greatly affects the possibility of oscillation.*

***When you find gremlins,** goblins, and bugaboos in your circuit, you have to exorcise them.*

(Heathkit makes one of these instruments whose updated name is "dip meter.") At that time I didn't have a 100-MHz scope, but I could see the rectified envelope of these high-frequency oscillations on a 25-MHz scope. So, if you see a circuit shift its dc level just because you move your finger near a transistor, you should become suspicious of high-frequency oscillations.

Of course, you will never "slide your finger around" in a circuit with high or lethal voltages.

One of the easiest ways to inadvertently cause a very-high-frequency oscillation is to run an emitter-follower transistor (even a nice, docile type such as a 2N3904) at an emitter current of 5 or 10 mA. In such a case, you can easily get an oscillation at a few hundred megahertz. So, although a good 100-MHz scope cannot spot this kind of oscillation, the resulting radiated noise can cause other circuits to go berserk and can cause an entire system to fail tests for radiated electromagnetic noise.

For such an emitter follower, a 50 or 100Ω carbon resistor directly in series with the base of the transistor (and *not* 2 or 3 in. away) can cure this tendency to oscillate. Sometimes a small ferrite bead is more suitable than a carbon resistor because it will degrade the transistor's frequency response less.

Not all problematic oscillations are high-frequency ones. An unstable switching-regulator feedback loop can oscillate at low frequencies. For troubleshooting switching-regulator feedback loops, I first recommend a network analyzer to save you troubleshooting time. A network analyzer facilitates taking data and checking out variations of the circuit in case of trouble. (However, I do tend to put more faith in real-time step response.)

Secondly, if an earlier version of your circuit has worked OK, what's the difference between the new one that does not work well and the old one that does? Be sure to keep one or more examples of the old version around so that you can make comparisons when the new circuits have troubles. (Note that I said *when*, not *if*.) Thirdly, look for components such as capacitors whose high-frequency characteristics can change if someone switched types or suppliers.

Optoisolators are another likely cause of oscillation trouble due to their wide range of dc gain and ac response. A switching-regulator IC, on the other hand, is not as likely to cause oscillations, because its response would normally be faster than the loop's frequency. But, the IC is never absolved until proven blameless. For this reason, you should have an extra module with sockets installed just for evaluating these funny little problems with differing suppliers, variant device types, and marginal ICs. You might think that the sockets' stray capacitances and inductances would do more harm than good, but in practice, you can learn more than you lose.

You can best analyze the design of a slow servo mechanism, such as that in **Fig 1,** with a strip-chart recorder because the response of the loop is so slow. (A storage scope might be OK, but a strip-chart recorder works better for me.) You might want to analyze such a servo loop with a computer simulation, such as Spice, but the thermal response from the heater to the temperature sensor is strictly a function of the mechanical and thermal mounting of those components. This relationship would rarely be amenable to computer analysis.

### Comparators can misbehave

Saying that a comparator is just an op amp with all the damping capacitors left out is an oversimplification. Comparators have a *lot* of voltage gain and quite a bit of phase shift at high frequencies, hence oscillation is always a possibility. In fact, most comparator problems involve oscillation.

Slow comparators, such as the familiar LM339, are fairly well behaved. And if you design a pc-board layout so that the comparator's outputs and *all* other large, fast, noisy signals are kept away from the comparator's inputs, you can often get a good clean output without oscillation. However, even at slow speeds, an LM339 can oscillate if you impress a slowly shifting voltage

ramp on its differential inputs. Things can get even messier if the input signals' sources have a high impedance (>10 kΩ) or if the pc-board layout doesn't provide guarding.

In general, then, for *every* comparator application, you should provide a little hysteresis, or positive feedback, from the output back to the positive input. How much? Well, I like to provide about twice or three times as much as it takes to prevent oscillation near the comparator's zero-crossing frequency. This excess feedback defines a safety margin. (For more information on safety margins, see the **box,** "Pease's Principle," in the September 1, 1989, edition of EDN.) I have never seen this hysteresis technique outlined in print, so you can say you read it here first.

My suggestion for excess hysteresis is only a rule of thumb. Depending on your application, you might want to use more hysteresis. For example, a comparator in an RC oscillator may operate with 1, 2, or 10V of hysteresis, which means you can always use more than my minimum amount of excess hysteresis. Also, if you have a signal with a few millivolts of noise, the comparator that senses the signal will often want to have a hysteresis range that is three times greater than the noise.

## Just the right touch

Comparators are literally very "touchy" components; that is, you can drastically alter their performance just by touching the circuit with your finger. And because

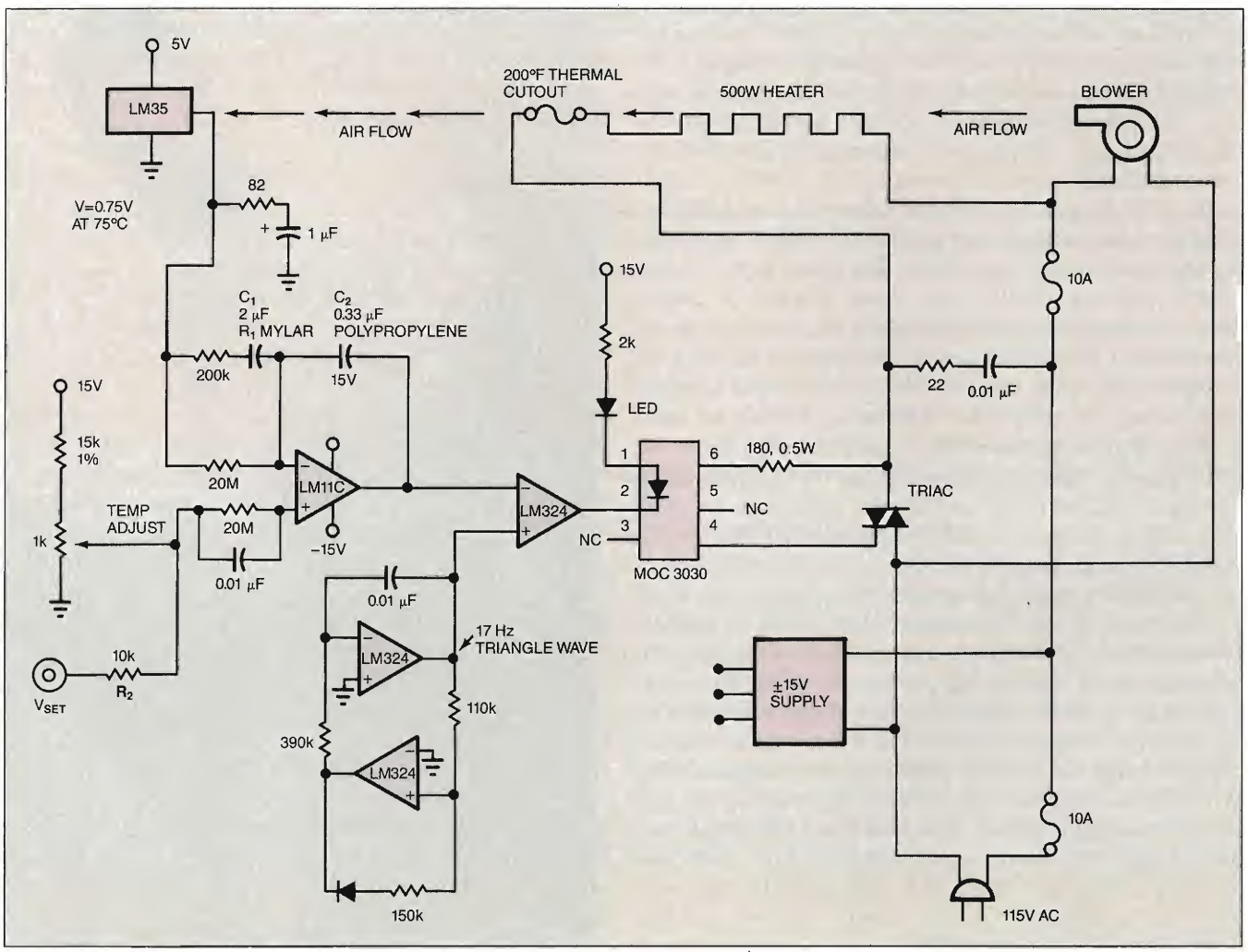



***Fig 1—Stabilizing this heater's*** *slow servo loop and choosing the proper values for $R_1$, $C_1$, and $C_2$ involved applying a 1V p-p, 0.004-Hz square wave, $V_{SET}$, to $R_2$ and observing the LM11C's output with a strip-chart recorder.*

*Merely stopping an oscillation is not enough; apply a tough stimulus to the circuit to see if it's safely removed from any tendency to oscillate.*

comparators are so touchy, you should be prepared for the probability that your safety margin may change, for better or worse, when you go from a breadboard to a printed-circuit layout. There's no way you can predict how much hysteresis you'll need when your layout changes, so you just have to re-evaluate the system after you change it.

For faster comparators, such as the LM311, everything gets even touchier, and the layout is more critical. Yet, when several people accused the LM311 of being inherently oscillatory, I showed them that with a good layout, the LM311 is capable of amplifying any small signal, including its own input noise, without oscillating and without any requirement for positive feedback. One special precaution with the LM311 is tying the trim pins (5 and 6, normally) together to prevent ac feedback from the output (pin 7, normally), because the trim pins can act as auxiliary inputs. The LM311 data sheet in the National Semiconductor Linear Databook has carried a proper set of advice and cautions since 1980, and I recommend this advice for *all* comparators.

With comparators that are faster than an LM311, I find that depending on a perfect layout alone to prevent oscillation just isn't practical. For these comparators, you'll almost certainly need some hysteresis, and, if you are designing a sampled-data system, you should investigate the techniques of strobing or latching the comparator. Using these techniques results in no direct path from the output to the inputs lasting for more than just a few nanoseconds. Therefore, oscillation may be evitable. Granted, heavy supply bypassing and a properly guarded pc-board layout, with walls to shield the output from the input, may help. But you'll probably still need some hysteresis.

For some specialized applications, you can gain advantages by adding ac-coupled hysteresis in addition to or instead of the normal dc-coupled hysteresis. For example, in a zero-crossing detector, if you select the feedback capacitor properly, you can get zero effective hysteresis at the zero-crossover point while retaining some hysteresis at other points on the waveform. The trick is to let the capacitor's voltage decay to zero during one half-cycle of the waveform. But make sure that your comparator with ac-coupled hysteresis doesn't oscillate if the incoming signal stops.

### Comparators *do* have noise

Data sheets don't talk about the noise of comparators, but comparators *do* have noise. Depending on which unit you use, you may find that each comparator has an individual "noise band." When a differential input signal enters this band slowly from either side, the output can get very noisy rail to rail, which results in amplified noise or oscillation. The oscillation can continue even if the input voltage goes back outside the range where the circuit started oscillating. Consequently, you can easily set up your own test in which your figure for offset voltage, $V_{OS}$, doesn't agree with the manufacturer's measured or guaranteed values. Indeed, it can be tricky to design a test that *does* agree.

For my tests of comparator $V_{OS}$, I usually set up a classic op-amp oscillator into which I build a specific amount of hysteresis and a definite amount of capaci-

Photographs by Peggi Willis

***It takes a lot of skill*** *and the right instrument to divine the source of perplexing problems.*

tance, so that the unit will oscillate at a moderate, controlled frequency. If you're curious, write to me for the details, which are not trivial.

Another way to avoid $V_{OS}$ trouble with comparators is to use a monolithic dual transistor as a differential-amplifier preamplifier stage ahead of the comparator. This preamp can add gain and precision while decreasing the stray feedback from the output to the input signal.

### Common-mode excursions unpredictable

After curing oscillation, most complaints about comparators are related to their common-mode range. We at National Semiconductor's applications engineering department get many calls from engineers who want to violate comparators' common-mode specs, but they're not always happy with our answers. I guess the complaints are partly the fault of the manufacturers for not being clear enough in their data sheets.

By way of contrast, most engineers know well that an op amp's common-mode-voltage range, $V_{CM}$, is defined provided that both inputs are at the same level. This spec makes sense for an op amp because most operate with their inputs at the same level. But in most cases, a comparator's inputs are not at the same level. As long as you keep both inputs within the comparator's specified common-mode range, the comparator's output will be correct.

But, if one input is within the common-mode range and the other is outside that range, one of three things could happen, depending on the voltages and the particular comparator involved. For some input ranges you can overdrive the inputs and still get perfectly valid response; for other input ranges, you can get screwy response but cause no harm to the comparator; and for others, you'll instantly destroy the comparator.

For example, for an LM339-type comparator running on a 5V supply, if one of its inputs is in the 0-to-3.5V range, then the other input can range from 0 to 36V without causing any false outputs or causing any harm to the comparator. In fact, at room temperature, the out-of-range input can go to $-0.1$V and still produce the correct output.

But, heaven help you if you pull one of the inputs below the $-0.1$V level, say to $-0.5$ or $-0.6$V. In this case, if you limit the comparator's input current to less than 5 or 10 mA, you won't damage the comparator. But even if no damage occurs, the outputs of any or all of the comparators in the IC package could respond falsely. Current can flow almost anywhere within the IC's circuitry when the substrate diode, which is inherent in the device's input transistor, is forward biased. It is this current that causes these false outputs.

***When oscillations get nasty**, you need a scope with pinpoint triggering to help you study the problem.*

We'll try to be more clear about $V_{CM}$ specs in the future. Maybe next time at National Semiconductor, we'll phrase the spec sheet's cautions a little more vigorously. Still, if you stay within their rated common-mode range, comparators are not that hard to put to work.

Of course, some people disdain reading data sheets, so they get unhappy when we tell them that differential signals larger than $\pm 5$V damage some fast comparators. But, this possibility has existed since the existence of the μA710, so you'll have to clamp, clip, or attenuate the input signal—differential or otherwise.

### An unmentionable problem

Something else that does *not* usually get mentioned in a data sheet are common-mode slew problems. The LM311 is one troublemaker, but to some extent all comparators can have these troubles. If one input suddenly slews up to exceed the other's level, you may see an unexpected, extra delay before the comparator's output changes state. This delay arises because the comparator's nodes do not slew fast enough internally for its outputs to respond. For example, a 10V step can accrue an extra 100-nsec delay compared with the the delay for a 100-mV step. And if both inputs slew together, the output can spew out indeterminate glitches or false pulses even if the differential inputs don't cross over. Be careful if your circuit cannot tolerate such glitches.

Come to think of it, I get occasional complaints from

*You should have an extra module with sockets just for evaluating funny little problems due to differing suppliers, variant device types, or marginal ICs.*

engineers along the lines of, "I've been using this comparator for years without any trouble, but suddenly it doesn't work right. How come?" When we inquire, we find that the comparators have been operating very close to the edge of the "typical" common-mode range, well beyond any guaranteed values. Although these engineers have been getting away with crowding the limits for years, the latest batch of comparators gives them trouble. Some of our best friends depend on us to have our parts meet those *typical* specs, and it's always painful for us to tell them that they really ought to depend only on *guaranteed* specs.

If you need three op amps and one comparator, can you use a single LM324? Well, op amps are not necessarily bad as comparators, but they sure are slow, and the LM324 is among the slowest. Not only is its slew-rate slow, but if you put in an overdrive of just 5 mV more than $V_{OS}$, the output will respond at only 0.01V/μsec—not even as fast as its specified slew rate. An LF351 or one fourth of an LF347 will respond somewhat faster. So if you want to use an op amp as a comparator, you'd better need merely a slow comparator. (Note, however, that one LM358 plus one LM392 will give you effectively three fourths of an LM324 plus one fourth of an LM339, and the space taken by the two 8-pin miniDIPs would be only 4% more than that taken by a single 14-pin DIP.)

But, even so, some people *do* use op amps as slow, precision comparators. Even though op amps are generally not characterized as comparators, you can engineer such a circuit successfully. For example, the LM709 minus its compensation capacitors is a surprisingly competent, fairly quick comparator. But, please don't overdrive and damage the inputs.

Conversely, I am occasionally asked, "Can I put some damping capacitors on an LM339 and use it as a unity-gain follower?" The general answer is NO! because the LM339's phase lags are too squirrelly to be controlled by any possible compensation scheme. But I have used the slower LP339 and LP365 successfully this way, as a slow inverter or slow follower.

### Even buffered circuits can oscillate

Any circuit that adds current gain can oscillate—even a buffer. Let's agree that a buffer is some kind of linear amplifier that has a lot of current gain. Some have a voltage gain around 0.90 or 0.95. Others have gains as high as 10 or 20 because their outputs must swing 50 or 100V p-p—or more. Even emitter followers, which you'd expect to be very docile because their

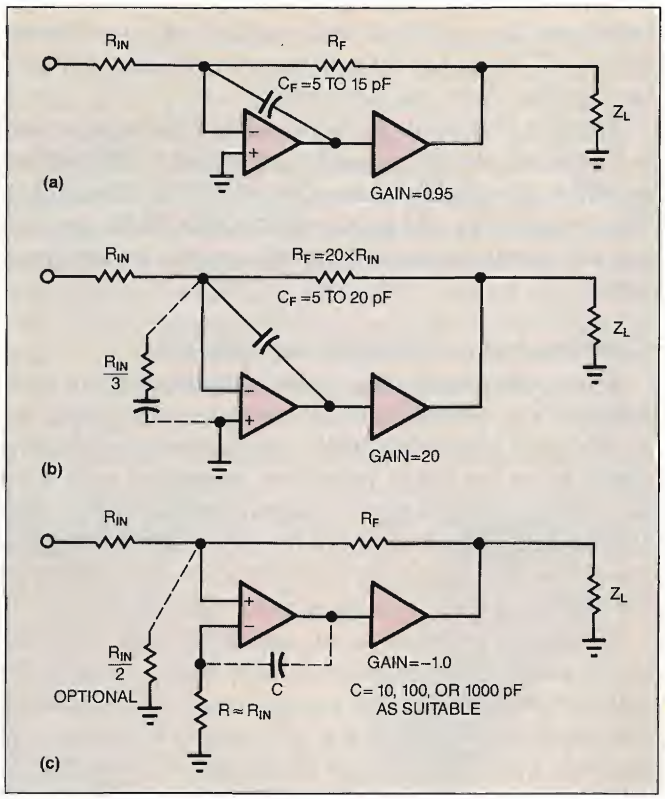



***Fig 2—Depending on the gain of the buffer,*** *you can use these three schemes to stabilize a buffered amplifier.*

voltage gain is less than 1, have a tendency to "scream" or oscillate at high frequencies. So whether you buy a buffer or "roll your own," watch out for this problem.

Also, a buffer can have a high-frequency roll-off whose slope increases suddenly at 40 or 60 MHz and thus can contribute phase shift to your loop back down at 6 or 10 MHz. You can beat this problem, but you have to plan. A buffer can also add a little distortion, which the op amp cannot easily cancel out at moderate or high frequencies. Since buffers don't usually have a spec on this distortion, beware. Also, if you're running the output's quiescent bias current as Class AB, you must be sure that the dc operating current is stable and not excessive. You must set it high enough so that you don't get distortion but not so high that power consumption becomes excessive.

One of my standard procedures for stabilizing a unity-gain follower stage is to put feedback capacitance around just part of the loop (**Fig 2a**). This circuit tolerates capacitive loads, because the buffer decouples the load while the feedback capacitor around the op amp provides local stability. Most unity-gain buffers,

*Comparators deserve the same degree of respect and amount of fair treatment as fast op amps do.*

whether monolithic, hybrid, or discrete, are unstable with inductive sources, so keep the input leads short. A series resistor may help stability, as it does for the LM310, but it will slow down the device's response.

Many high-speed buffers have the chore of driving loads in the range of 50 to 150Ω. Driving these loads can require a lot of current, which leads to overheating. Plan your heat sinks carefully to keep the device from exceeding its rated maximum temperature. Most buffers don't have any thermal shutdown feature, but the new LM6321s and LM6325s show that an op amp, at least, can have such features designed in. When using buffers to drive remote loads, be sure that the transmission lines or cables have suitable termination resistances on both ends to prevent reflections and ringing. If you can afford the voltage drop, it's best to put about 50Ω between the buffer and its cable.

When your buffer provides a lot of extra voltage gain, you must make sure that the gain rolls off in a well-engineered way at high frequencies, or the loop will be unstable. If the buffer-amplifier has a positive gain, as in **Fig 2b,** you can use capacitive feedback around the main amplifier. But when the buffer-amplifier has a gain of −10 **(Fig 2c)**, you may want to apply a feedback capacitor from the output of the buffer-amplifier to the noninverting input of the op amp. In some cases, you can achieve stability by putting a series RC damper from the noninverting input to ground to increase the noise gain, but this trick doesn't always work. Damping this loop is not easy.

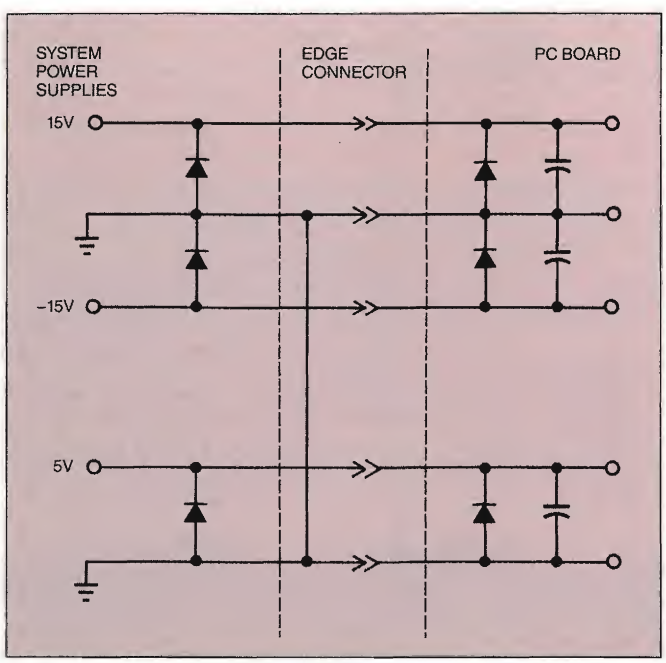



***Fig 3—Installing antireversal diodes*** *in the system power supplies and on each pc board greatly reduces the chance of damaging the supplies or the circuitry with inadvertent short circuits or polarity reversals.*

A circuit that inadvertently latches up presents a problem exactly opposite that of an oscillating circuit. Or, you could correctly say that a latched-up circuit is an oscillator with zero frequency. Although latched-up circuits demand troubleshooting, the good thing about them is that they sit right there and let you walk up to them and touch them. And you can measure everything with a voltmeter to find out how they became latched. This state of affairs doesn't mean that troubleshooting them is easy, because sometimes you can't tell how the latched-up circuit got into its present state. And in an integrated circuit, there can be paths of carriers through the substrate that you can't "put your finger on."

The worst aspect of latched-up circuits is that some are destructive, so you can't just sit there and let them remain latched up forever. Two approaches for attacking destructive latches are:

- Turn off the power quickly, so the latched-up circuit cannot destroy anything. Try turning on power for short pulses and watching the circuit as it *approaches* the destructive latch condition.
- Use an adjustable current-limited supply with a zero or small output capacitance, so when the circuit starts to latch, the fault condition can easily pull the current-limited power supply's voltage down.

Another way to inadvertently generate a latched-up condition is to turn on the outputs of your multiple-output power supply in the "wrong" sequence. Some amplifiers and circuits get quite unhappy when one supply (usually the positive one) turns on first. Automatic power-supply sequencers can help you avoid this problem. An antireversal rectifier across each supply can help, too, and is always a good idea for preventing damage from inadvertently crossed-up power-supply leads or supply short circuits.

I used to get calls every few months from people who asked me if it was okay to ship products that contained LM108s that may have had +15V on their −15V pins and vice versa. Telling them, "Don't ship it—junk it. And, next time put antireversal diodes on each supply," was always painful for me. Specifically, you should add these antireversal rectifiers across each bus in your system to protect the loads and circuits. Also add an antireversal rectifier across each power

supply to protect the supplies (**Fig 3**). Some people think that leaving parts out is a good way to improve a circuit's reliability, but I've found that putting in the right parts works best.

If you have any doubt that your fixes are working, try heating or cooling the suspected semiconductor device. Don't bother heating passive components such as resistors, capacitors, and inductors because their characteristics don't change enough with temperature to matter. Even if a circuit doesn't get better when heated, it can get worse when cooled, so also take a peek at the circuit while applying some freeze mist.

My point is that merely stopping an oscillation is not enough. You must apply a tough stimulus to the circuit and see whether your circuit is close to oscillation or safely removed from any tendency to oscillate. This stricture applies not only to regulators but also to all other devices that need oscillation-curing procedures.

For example, if a 47Ω resistor in the base of a transistor cures an oscillation, but 24Ω doesn't, and 33Ω doesn't, and 39Ω still doesn't, then 47Ω is a lot more marginal than it seems. Maybe a 75Ω resistor would be a better idea—just so long as 100 or 120 or 150Ω resistors are still safe.

In other words, even though wild guesses and dumb luck can sometimes cure an oscillation, you cannot cure oscillations safely and surely without some thoughtful procedures. Furthermore, somebody who has an appreciation for the "old art" will have the best results.

I certainly do not want to say that technicians can't troubleshoot oscillations simply because they don't know the theory of why circuits oscillate—that's not my point at all. I will only argue that a green or insensitive person, whether a technician or an engineer, can fail to appreciate when a circuit is getting much too close to the edge of its safety margins for comfort. Conversely, everyone knows the tale of the old-time unschooled technician who saves the project by spotting a clue that leads to a solution when all the brightest engineers can't guess what the problem is. EDN

## Author's biography

*For more information about Bob Pease, see the* ***box,*** *"Who is Bob Pease, anyway?" on page 148 of the January 5, 1989, edition of EDN.*

Article Interest Quotient (Circle One)
High 479 Medium 480 Low 481

**PART 10**

# The analog/digital boundary needn't be a never-never land

*Past installments have dealt with circuit elements and circuits usually thought of as purely analog. Now Pease turns to an area that confounds and frightens all too many engineers—the boundary between the analog and digital worlds. Armed with a solid theoretical foundation and the insights presented here, you can keep your journey into the analog/digital world from seeming like a visit with Peter Pan.*

Robert A Pease, *National Semiconductor Corp*

Many classes of circuits are neither entirely analog nor entirely digital. Of course, as an analog engineer, I don't have a lot of trouble thinking of *all* circuits as analog. Indeed, when problems develop in circuits containing both analog and digital elements, finding a solution is more likely to require that you summon your analog expertise than your digital knowledge. Timers, D/A and A/D converters, V/F and F/V converters, and S/H circuits all fall right on the boundary line between the analog and digital worlds. Digital ICs have more than a few analog subtleties. And even multiplexers, which you may have thought of as purely analog, have some quirks that result from their close association with the digital world.

A timer is basically a special connection of a comparator and some logic. The familiar 555 timer can do a lot of useful things, but it sure does get involved in a great deal of trouble. I'll treat the most classical fiascoes.

For one thing, people try to make timers with the crummiest, leakiest—usually electrolytic—capacitors. Then they complain because the timers are not accurate or their timing isn't repeatable. Some people insist on building timers to run for many seconds and then have trouble tweaking the time to be "exactly right." Sigh. These days I tell people, "Yes, you *could* make a 2-minute timer with an LM555 or a 10-minute timer with an LM322, but that would be WRONG." Instead, you could make a simple 1-Hz oscillator using one-quarter of an LM324 or LM339 and cheap, small components. This oscillator can drive a CD4020 or CD4040; the last output of that counter, $\div 2^{12}$ or $\div 2^{14}$, can time very accurately and conveniently.

Such an arrangement is cheaper and much more accurate and compact than what you get if you blow a lot of money on a 47-μF polyester capacitor for a long-interval timer, or put up with the leakages of a tantalum capacitor, which no manufacturer wants to guarantee. In addition, in just a few seconds, you can trim the moderate-frequency oscillator by looking at an early stage of the divider; trimming a long-interval timer can take hours. The CMOS counters are inexpensive enough, and these days for 2- to 20-minute timer applications, I can usually convince customers *not* to buy the linear part.

The LM555 data sheets tell you to avoid timing resistors with values higher than 20 MΩ. Nowadays, though, you can get a CMOS version (LMC555 or

*People try to make timers with the crummiest, leakiest—usually electrolytic—capacitors. Then they complain because the timers are not accurate.*

equivalent) or use a CMOS comparator or a CMOS op amp to work at 100 MΩ or more. Just be careful about board leakage and socket leakage—as you would with a high-impedance op-amp circuit. Then you can use a smaller, higher-quality capacitor.

Furthermore, it is a nontrivial statement that not all 555s work similarly; some manufacturers' 555s have different internal circuits and different logic flow charts. So be careful to check things out—555s from different manufacturers can act quite differently.

At high speeds, the timers don't just respond in a time $R \times C$; the response time is more like $R \times (C + C_{STRAY}) + T_{DELAY}$. Most books never mention this fact. So, although you can usually get a circuit to function, to get it to work the way you want it to, you still have to be careful. These designs are not always trivial, and **Ref 1** may help you avoid some pitfalls. A timer is, after all, just an aggregation of parts that includes a comparator, so many of the techniques you use with comparators work with timers and vice versa.

### Digital ICs: not purely digital

Although timers are partly digital, the more classic digital ICs perform purely logical functions. Nevertheless, in the hands of a clever "linear" designer, some digital ICs can be very useful for performing analog functions. For example, CD4066 quad analog switches make excellent low-leakage switches and a 74C74 makes an excellent phase detector for a phase-locked loop (**Ref 2**). And not only is the price right—so is the power drain. Even when ordinary CMOS ICs aren't fast enough, you can often substitute a high-speed CMOS or 74ALS or 74AS counterpart to get more speed. I won't belabor the point; instead, I'll go straight to the litany of Troubles and Problems that you—whether an analog or a digital designer—can encounter with digital ICs.

First, unless proven otherwise, you should have one *ceramic* power-supply bypass capacitor in the range 0.02 to 0.2 μF—or even 1 μF, if the IC manufacturer requires it—for each digital IC *plus* a tantalum capacitor in the range 2 to 10 μF for every two, three, or four ICs. The ceramic capacitors provide good high-frequency bypassing; the tantalum parts damp out the ringing on the power-supply bus. If you can't use a tantalum capacitor, you can try a 1- or 2-μF extended-foil Mylar unit in series with a 1Ω carbon resistor. If your linear circuit really depends on clean, crisp digital outputs (CMOS outputs make dandy squarewave generators, as long as the power supply isn't ringing and bouncing) you may even want more bypassing—possibly hundreds of microfarads.

### Floating inputs can leave you at sea

On TTL parts, you can leave an unused input floating and it will go high; on CMOS, you must tie unused inputs (such as the preset and clear inputs of a flip-flop) to the positive supply or ground, as appropriate. Otherwise, these inputs will float around and give you the screwiest intermittent problems. Also, when these inputs float, for example, on unused gates, they can cause considerable unwanted power drain and self-heating.

With CMOS, people keep telling you that you can use an inverter as an amplifier by tying a few megohms from the input to the output. At low voltages, you *can* make a mediocre amplifier this way, but when the supply voltage is above 6V, the power drain gets pretty heavy and the gain is low. I don't recommend this approach for modern designs.

Many years ago, people used to tie the outputs of DTL or open-collector TTL gates together to form a "wired OR" gate. This practice has fallen into disrepute as it supposedly leads to problems with troubleshooting. I don't know what other reason there is for not doing it except to avoid acting like a nerd. However, an open-collector output with a resistive pullup is slower than a conventional gate and wastes more power.

When digital-circuit engineers have to drive a bus for a long distance, say 20 or 30 inches, they use special layouts, so the bus will act like a 50Ω stripline. They also add termination resistors at one or both ends of the bus to provide damping and to cut down on reflections and ringing. When you have to drive long lines in an analog system, you should do the same. Note that for really fast signals, digital designers don't even lay out their pc traces with square corners; they bend the foil around the corner in a couple of 45° turns. Many digital engineers are not just bit-pushers; they've been learning how to handle real signals in the real world. They are actually pretty expert in some analog techniques, and analog engineers can learn from them.

### Perfect waveforms don't exist

Even though many digital engineers are familiar with real problems, they often sketch the waveforms from gates and flip-flops showing nice, crisp, vertical rises and showing the output of a gate changing at the same time as the input. But smart engineers are aware

that when it comes down to the fine print, they must be prepared to admit that these waveforms have finite rise times and delays. These nit-picking details are very important when your signals are in a hurry.

For example, if the data input of a D flip-flop rises just before you apply the clock pulse, the output goes high. If the data input rises just after you apply the clock pulse, the output goes low. But if the D input moves at *just* the wrong time, the output can show "metastability"—it can hang momentarily half way between high and low and take several dozen nanoseconds to finally decide which way to go. Or, if the data comes just a little earlier or later, you might get an abnormally narrow output pulse—a "runt pulse".

When you feed a runt pulse to another flip-flop or counter, the counter can easily respond falsely and count to a new state that might be illegal. Thus, you should avoid runt pulses and make sure that you don't clock flip-flops at random times. **Fig 1a** contains an example of a D flip-flop application that can exhibit this problem. When the comparator state changes at random times, it will occasionally change at precisely the wrong time—on the clock's rising edge—making the output pulse narrower or wider than normal. In certain types of A/D converters, this effect can cause nonlinearity or distortion. A good solution is to use a delayed clock to transfer the data into a second flip-flop, as in **Fig 1b**.

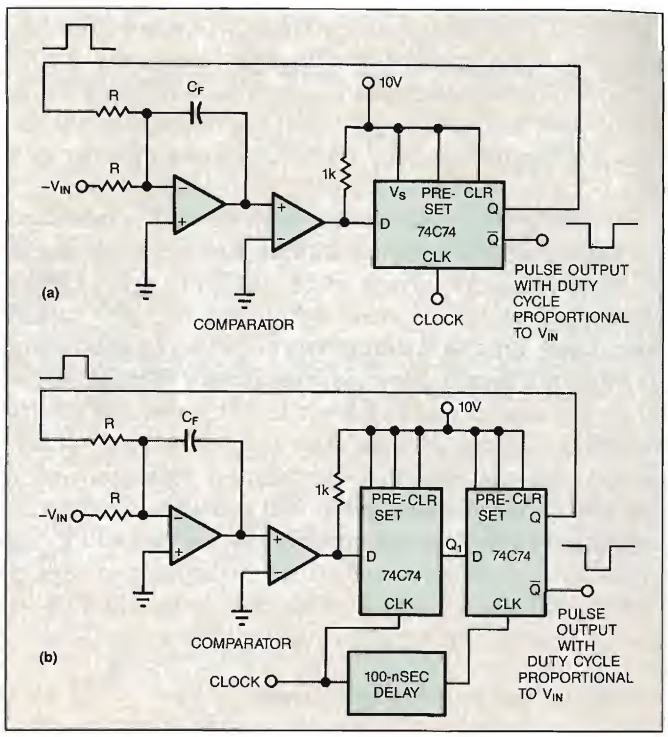



***Fig 1—Runt pulses cause problems** in this simple ADC **(a)**. The comparator state changes at random times. Occasionally, the state will change at precisely the wrong time—on the clock's rising edge—making the output pulse narrower or wider than normal. You can solve the problem by using two flip-flops with the clocks separated by a delay **(b)**.*

A glitch is an alternate name for a runt pulse. A classic example of a glitch occurs when a ripple counter, such as a 7493, feeds into a decoder, such as a 7442. When the counter makes a carry from 0111 to 1000, for a few nanoseconds the output code will be 0000, and the decoder can spit out a narrow pulse of perhaps six to eight nanoseconds in duration corresponding to 0000. Even if you are observing with a good scope, such a pulse can be just narrow enough to escape detection. If the decoder were merely feeding an LED display, you would never see the submicrosecond light pulse, but if the decoded output goes to a digital counter, a false count can occur. In digital systems, engineers often use logic analyzers, storage scopes, and scopes with very broad bandwidths to look for glitches or runt pulses and the conditions that cause them. In analog systems, you may not have a logic analyzer, but these nasty narrow pulses often do exist, and you have to look for them.

Another thing to know about digital ICs is that many CMOS ICs have the same pinouts as TTL parts. For example, the 74193, 74LS193, and 74C193 have the same pinouts. On the other hand, some of the older CMOS parts have pinouts that differ from those of similarly numbered TTL devices. The 74C86's pinout is the same as the 74L86's but differs from the 7486's. Beware!

Similarly, some CMOS devices have many—but not all—of their functions in common with those of their TTL counterparts. For example, the 74C74 has the same pinout and 98% of the same functions as the 7474. Both follow mostly the same truth table, *except* that when you pull both the preset and clear inputs low, the TTL device's outputs (Q and $\overline{Q}$) both go low, whereas the CMOS part's outputs both go high. If anybody has a complete list of such differences, I'd *love* to get a copy.

In some cases you can buy a buffered gate (CD4001BN), an unbuffered gate (CD4001), an unbuffered inverter (MM74HCU04), or a buffered inverter (MM74HC04). Sometimes, you can buy one part number and get an unbuffered part from one vendor

*Digital engineers have been learning to handle real-world signals. They're experts in some analog techniques, and analog engineers can learn from them.*

and a buffered one from another. Of course, the unbuffered parts are faster with light capacitive loads, but the buffered ones are faster with heavy loads. So if you have a critical application, be aware that substituting different vendors' parts can mess up your circuit.

Be careful when interfacing from linear ICs into digital ones. For example, an LM324 running on a single 5V supply doesn't have a lot of margin to drive CMOS inputs, but an op amp running on ±5 or ±10V would need some kind of attenuation or resistive protection to avoid abusing the logic-device inputs (**Fig 2**). Likewise, it's considered bad form to overdrive the inputs of digital ICs just because they are protected by clamp diodes. For example, you *can* make a pulse generator per **Fig 3**, but it's considered bad practice to drive the inputs hard into the rail and beyond, as you will if the capacitance is more than 0.01 μF or the power supply voltage is higher than 6V. The circuits in **Fig 4** do as good a job without overdriving the inputs.

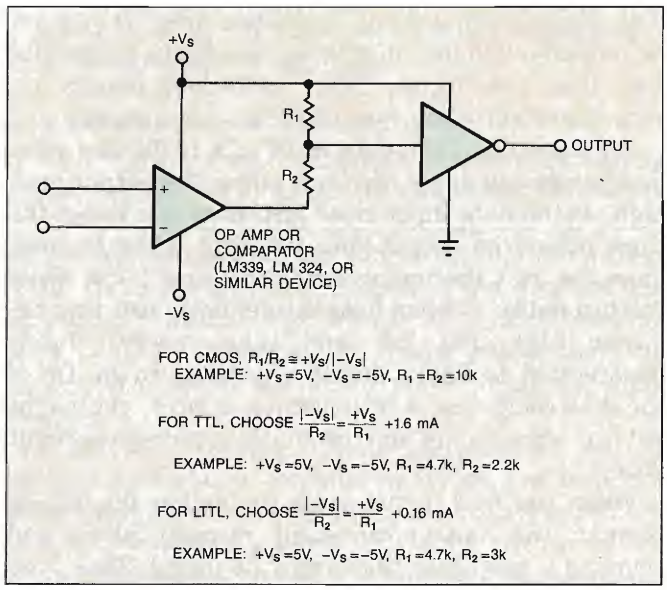



***Fig 2—Driving logic from an op amp*** *operating from the usual large supply voltages requires an attenuator between the amplifier and the logic IC. The equations show how to calculate the attenuator ratios.*

### A time to ask probing questions

A number of years ago, I was watching the negative transition of an ordinary TTL gate, and I was especially concerned by the way it was overshooting to −0.4V. I set up an attenuator with 1 pF in the input leg (**Fig 5**), and was astounded to see that if I looked at the waveform with an ordinary (11-pF) probe, the overshoot occurred, but if I disconnected the probe from the gate output and connected it to the attenuator output, the overshoot went away. So, even if you use a fairly high-impedance probe, you should always be prepared for the possibility that by looking at a signal,

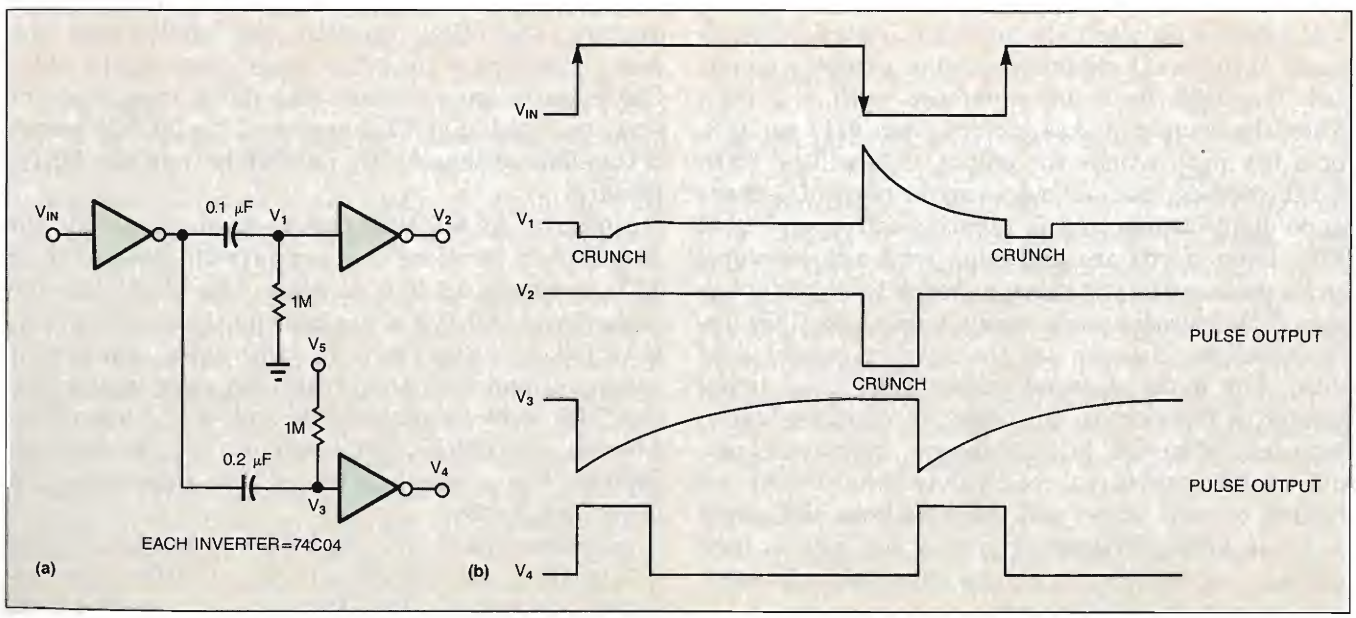



***Fig 3—This CMOS pulse generator (a)*** *is not recommended because, with the values shown, it overdrives the gate inputs excessively—as the waveforms of* ***b*** *indicate.*

you can seriously affect it—even if what you're looking at is as mundane and supposedly robust as a TTL output. Consequently, you should be prepared to build your own special-purpose probes, so you can see what's *really* going on.

When I work with digital ICs, I would be easily confused if I did not sketch the actual waveforms of the ICs to show their relationships to each other. So I sketch these waveforms on large sheets of quadrule paper (¼-in. grid) to produce something I call a "choreography" because it maps out what I want all the signals to do and exactly where I require them to dance or pirouette . . . When the system gets big and scary, I sometimes tape together two or three or four sheets horizontally and as many sheets as I need vertically. Needless to say, I am not very popular when I drag one of these monsters up to the copying machine and try to figure out how to make a copy. **Fig 3b** is a small example.

Maybe the guys who design really big digital ICs can get along without this technique; maybe they have other mnemonic tools, but this one works for me. I first developed this approach the time I designed a 12-bit monolithic ADC, the industry's first, back in 1975. I had this big choreography, about 33-in. square, and the circuit worked the first time because the choreography helped me avoid crossing up any digital signals. Right now I'm working on a system with one choreography in nanoseconds and tenths of nanoseconds linked to a second one scaled in microseconds and a third one scaled in seconds. I hope I don't get lost.

Of course, this tool is partly for design, but it's also a tool for troubleshooting—and for planning, so you can avoid trouble in the first place.

### DACs are generally docile

DACs are pretty simple machines, and they can usually give excellent results with few problems. What kind of trouble can you get into with a DAC? If the manufacturer designed it correctly *and* you are not misapplying it, a DAC usually won't cause you much grief.

One area where DACs *can* cause trouble, however, is with noise. Most DACs are not characterized or guaranteed to reject high-frequency noise and jumps on the supply voltages. In some cases, the dc rejection can be 80 or 100 dB, but high-frequency noise on a supply can come through to the output unattenuated. So you must plan your system carefully. It might be

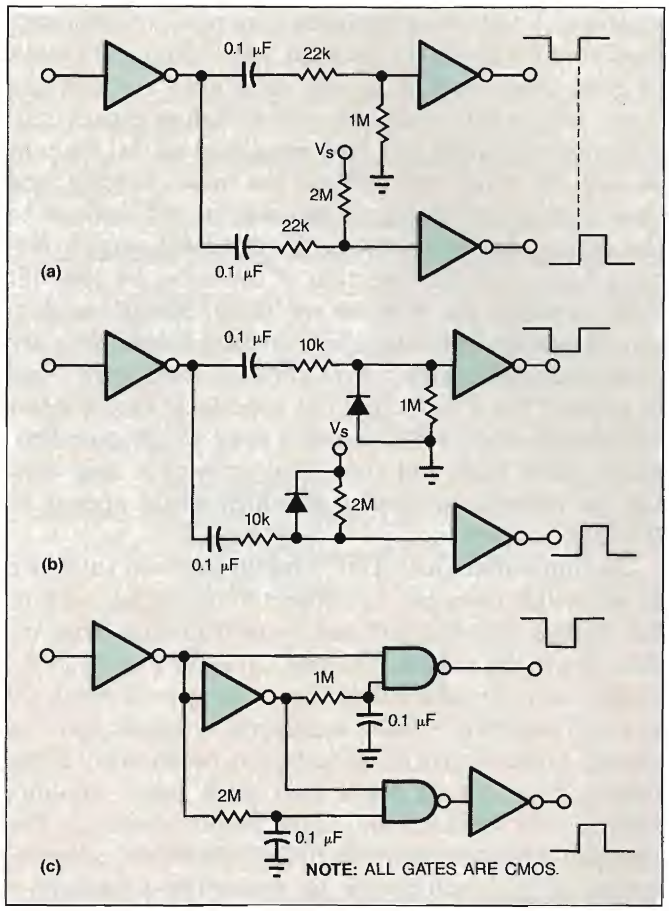



***Fig 4—The addition of attenuators** to the circuit of Fig 3 **(a)** helps reduce overdrive, but the addition of diode clamps in the shunt leg of the attenuators **(b)** is even more effective. If you have two 2-input NAND gates available, the circuit of **c** is the best implementation.*

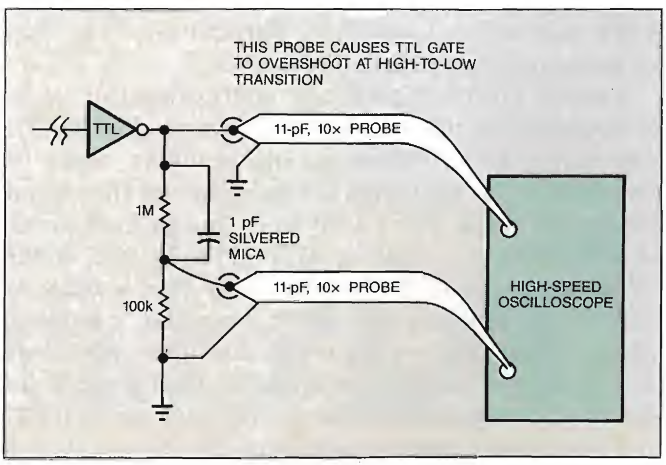



***Fig 5—An ordinary high-impedance probe** can cause TTL outputs to ring. You can eliminate this effect by cascading such a 10× probe with an attenuator of your own that presents a 1-pF capacitive load.*

*You should always be prepared for the possibility that by looking at a signal, you can seriously affect it.*

a good idea to use a completely separate power-supply regulator for the DAC. At least you should add plenty of good power-supply bypass capacitors right at the power-supply pins—ceramic *and* tantalum capacitors.

Sometimes when you feed signals to a DAC without passing them through buffers, the noise, ringing, and slow settling of the digital signals can get through to the analog side and show up on the DAC output. Nobody has a spec for rejection of the noise on DAC bit lines in either the high or low state. Maybe vendors should specify this parameter, because some DACs are good and some aren't. I even recall a case where I had to preload the TTL outputs of a modular DAC's internal storage register. Otherwise they would overshoot when going high and then recover with a long slow tail, an attenuated version of which would appear on the DAC output.

On-chip buffers at a DAC's input can help cut down feedthrough from the bit lines to the analog output, but buffers usually can't reduce feedthrough from the data bus to the output. The bus can move around incessantly, and capacitive coupling or even pc-board leakage will sometimes cause significant crosstalk into the analog world. Even IC sockets can contribute to this noise. If you could prove that such noise wouldn't bother your circuit, you could forget about it. The problem is that you can only make meaningful measurements of such effects on an operating prototype—computer modeling can't simulate *everything*.

Multiplying DACs are popular and quite versatile. However, a multiplying DAC's linearity can be degraded if the output amplifier's offset voltage isn't zero. I've heard this degradation of linearity estimated at 0.01% per millivolt of offset. Fortunately, low-offset op amps are pretty cheap these days.

Another imperfection of any multiplying DAC is its ac response for different codes. If you put in a 30-kHz sine wave as the reference, you shouldn't really be surprised if the gain from the reference to the output changes by more than 1 LSB when you go from a code of 1000 0000 to a code of 0111 1111. In fact, if the frequency is above 5 kHz, you may find a 0.2% or larger error because the multiplying DAC's ladders, whose attenuation is a linear function of the input code at dc, become slightly nonlinear at high frequencies due to stray capacitance. The nonlinearity can be 0.2%, and the phase change as you vary the input code can exceed 2°, even with a 5-kHz reference. So don't let these ac errors in multiplying DACs surprise you.

Another problem with DACs is the output glitch they can produce when going from one code to an adjacent one. For example, if a DAC's input code goes from 1000 0000 to 0111 1111 and the delay for the rising bits is much different from that for the falling bits, the DAC output will momentarily try to go to positive or negative full scale before it goes to a value corresponding to the correct code. Though well known, this problem is a specialized one. The solution requires precisely synchronous timing. Multiple storage registers can also help to save the day. If the best synchronous timing is not good enough, a deglitcher may be the solution.

### ADCs can be tough and tempermental

Like DACs, many ADCs do exactly what they are supposed to, so what can go wrong? Most problems involve a characteristic that is mentioned on too few data sheets: noise. When an analog signal moves slowly from one level to another, it would be nice if the ADC put out only the code for the first voltage and then, at the appropriate threshold, began to produce only the code for the other voltage. In practice, there is a gray area where noise causes codes to come up when they shouldn't. On a good ADC, the noise can often be as low as 0.1 LSB p-p. But when you come to a worst-case condition (which with successive-approximation converters often occurs at or near a major carry—for example, where the output changes from 1000 0000 to 0111 1111), the noise often gets worse, sometimes climbing to 0.5 LSB p-p or more. I wouldn't want to buy an ADC without knowing how quiet it was. I'd have to measure the noise myself, as shown in **Fig 6**, because virtually nobody specifies it. That's not to say all ADCs are bad, just that manufacturers don't make much noise about noise.

Ron Knapp of Maxim wrote a nice explanation of an ADC noise measurement technique in EDN late last year (**Ref 3**). I recommend his article on this subject.

Most ADC data sheets spell out that the only correct way to test or use an ADC is with the analog signal's ground, the digital supply's ground, and the analog supply's ground tied together right at the ground pin of the ADC. If you don't or can't interconnect the grounds at the specified point, all bets are off.

### With ADCs, paper designs aren't adequate

On one 10-bit ADC I designed, when the customer found some problems that I couldn't duplicate in my lab, I bought one plane ticket for me and one for my best scope. After a few hours we arrived at the scene,

and in less than an hour I had the problem defined: The customer expected our converter to meet all specs with as much as 0.2V dc plus 0.2V ac, at frequencies as high as 5 MHz, between the analog ground and the digital ground. Amazingly, our architecture was such that by deleting one resistor and adding one capacitor, I could comply with the customer's wishes. Most ADCs couldn't have been made to work—the customer was fantastically lucky that I had used a weird design that was amenable to this modification. My design was a high-speed integrating converter with an input voltage-to-current converter that just happened to be capable of rejecting wideband noise and dc offsets between grounds.

The general lesson is that any ADC system is nontrivial and should be engineered by actually plugging in

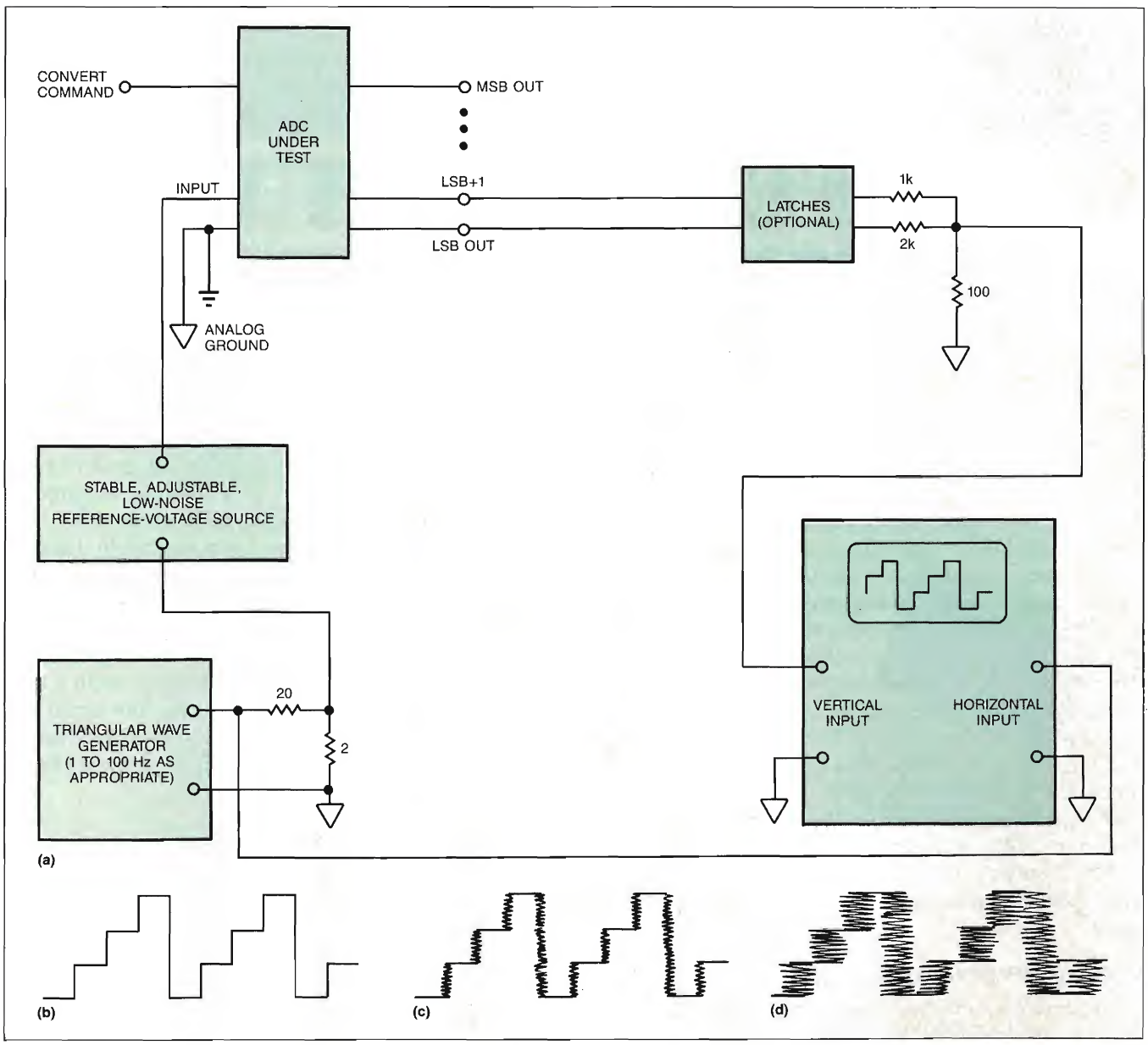



***Fig 6—A reference source,*** *a triangular-wave generator, and a scope are the major building blocks of an ADC crossplot tester* ***(a)*** *that can reveal how much noise a converter adds to the signal it is digitizing. In* ***b,*** *the noise performance is ideal, whereas in* ***c,*** *it is merely acceptable. In* ***d,*** *the noise performance is unacceptable.*

*Most DACs are not characterized or guaranteed to reject high-frequency noise and jumps on the supply voltages.*

some converter circuits. "Paper designs" usually don't hold water in ADC systems.

To beat the requirement that every ADC have its own set of power supplies dedicated exclusively to powering just the single converter, you may want to bring power to your pc boards in unregulated or crudely regulated form and put a small regulator right near each ADC. These small regulators (whether LM320, μA7800, LM317, or whatever) do *not* have a high power-supply rejection ratio at high frequencies. You can resolve that problem with decoupling, so you have a chance to make the scheme work. I hasten to point out, however, that I haven't actually built such a system myself.

### Don't let ground loops knock you for a loop

The need for multiple power supplies, or at least multiple regulators, comes, of course, from the many paths taken by ground currents flowing to and from the power supplies. If you don't keep these paths scrupulously separate, the ground loops can cause bad crosstalk between various parts of the system—low-level analog, high-power analog, and digital. So be very careful to avoid ground loops when you can. Although the electrical engineering faculty at your local university might not agree, a general solution to the ground-loop problem would be an excellent subject for a PhD thesis. If you write such a dissertation, please don't forget to mail me a copy.

Some successive-approximation ADCs have separate buffers feeding their output pins, but other designs try to save money, parts, power, or space by using the internal registers to drive both the internal DAC and the output pins. In this case, external loads on the outputs can cause poor settling and noise and can thus degrade the performance of the converter. If you're using ADCs, you should find out if the outputs are connected directly to the DAC. Sometimes, as previously mentioned, preloading the bit outputs helps to accelerate settling of an ADC's internal DAC. After all, TTL outputs must be able to drive more current than their dc specs state—they have to meet their ac specs.

### VFCs and FVCs frequently find favor

The voltage-to-frequency converter (VFC) is a popular form of ADC, especially when you need isolation between the analog input and digital outputs. You can easily feed a VFC's output pulse train through an optoisolator. The VFC can cover a wide range with 14 to 18 bits of dynamic range. The less expensive VFCs are slower; the faster ones can be expensive. Most VFCs have excellent linearity, but the linearity depends on the timing capacitor having a low dielectric absorption. Teflon makes the best VFC timing capacitors, but polystyrene, polypropylene, and ceramic capacitors with a C0G characteristic are close behind.

Trimming a VFC to get a low temperature coefficient is not easy because the overall temperature coefficient depends on several components, including the reference, as well as various timing delays. See **Ref 4** for VFC trimming procedures or, at least, to appreciate how much effort is involved when you buy a well-trimmed unit.

Frequency-to-voltage converters (FVCs) are often used as tachometers or in conjunction with a VFC and an optoisolater to provide voltage isolation in an analog system. FVCs are about as linear as VFCs and about as drifty, so the temperature trimming problem is the same as for a VFC. One exception is if you're using cascaded VFC/FVC pairs in which both circuits are in the same location and at the same temperature. In that case, you can often get by with trimming only one of the pair.

Another problem with FVCs is that you often want the response to be as fast as possible but need to keep the ripple low. The design of a filter to accomplish both objectives will, of course, be a compromise. My rule of thumb is that you can keep the ripple down to about 0.01% of the $V_{FULLSCALE}$, but with the simplest filters, you must keep the carrier at least 100 times the $F_{-3\ dB}$. With more sophisticated filtering, such as two Sallen-Key filters cascaded, the −3-dB point can be 1/10 of the slowest carrier. For example, with a carrier frequency in the range 5 to 10 kHz, the signal can go from dc to 500 Hz (**Ref 5**). If you need still faster response, see **Ref 2,** which shows how to use a phase-locked loop to make a quick FVC.

### S/H circuits: electronic stroboscopes

A VFC produces an output proportional to the average value of its analog input during the conversion. If you need to digitize rapidly changing signals, for example, to reconstruct waveforms in the digital domain, you need a different type of ADC and you almost always have to precede it with a sample-and-hold circuit. Designing S/H circuits is a complicated, challenging endeavor. Meeting exacting specs often requires an expensive module or hybrid circuit. A major problem of S/H circuits is dielectric absorption, or "soakage,"

*On-chip buffers at a DAC's input can help cut down feedthrough from the bit lines to the output but usually can't reduce feedthrough from the data bus to the output.*

in the hold capacitor (**Ref 6**).

If you need to run a relatively short sample time with a long hold time and if the new output voltage can vary considerably from the previous sample, the soakage may be your biggest problem. For example, if an S/H circuit acquires a new voltage for 5 μsec and then holds it for 500 μsec, you can tell approximately what the previously held signal was because the new $V_{OUT}$ can shift by 2 to 3 mV—the amount and direction depend only on the value of the previous signal. And that's for an expensive Teflon hold capacitor—most other capacitors have soakages three to five times worse. If the timing doesn't change, you may be able to add a circuit to provide some compensation for the soakage (**Ref 7**); but the problem isn't trivial, and neither is the solution. Cascading two S/H circuits—a fast one and a slow one with a big hold capacitor—won't help the soakage but will tend to minimize the problem of leakages.

Some people wish that a S/H circuit would go from sample to hold with a negligible jump, or "glitch." Although you *can* build such a circuit, it's a lot more difficult than building a more conventional S/H circuit. You usually find glitch-free S/H circuits only in "deglitchers," which are more expensive than most S/H circuits. Several module and hybrid manufacturers provide this kind of precision device. Even though it doesn't settle out instantly, a deglitcher is fast and consistent in its settling. However, it still does take some time to settle within 5 mV.

### Aperture time still causes confusion

There's one area of specsmanship where the S/H circuit is clouded in confusion. That area is the aperture-delay specification. (Maybe someday I'll write a data sheet and drive away the cloud.) One technique for measuring and defining aperture delay is to maintain $V_{IN}$ at a constant level and issue the hold command. If after a short delay, $V_{IN}$ jumps by a few volts, the smallest spacing between the hold command and the $V_{IN}$ jump that causes no false movement of $V_{OUT}$ is one possible definition of the $t_{APERTURE\ DELAY}$.

Another way of defining and measuring aperture delay might be to let $V_{IN}$ move smoothly at a well-defined rate. Shortly after you issue the command to switch the circuit to the hold mode, $V_{OUT}$ stops changing. The value at which $V_{OUT}$ stops corresponds to the value of $V_{IN}$ at a particular point in time. You can define the aperture delay as the difference between this point and the point at which the mode-control signal crossed the logic threshold. The uncertainty in the value of the aperture delay is then the aperture uncertainty. Depending on how the circuit was optimized, that delay can be positive *or* negative *or* practically zero—perhaps only 1 nsec or less. Now, will the *real* definition of aperture time please stand up?

Photographs by Peggi Willis

***Pease irritates coworkers*** *when he carries one of his "choreographies" to the photocopier and tries to figure out how to duplicate such a large drawing.*

I think that both of the characteristics I have described are of interest to people at different times. But, how can you avoid the problem of a person expecting one of these characteristics and actually getting the other? I invite your comments on who wants to buy which characteristic, and where to find a definition. I've looked in military specs and at many data sheets, and the issue still seems pretty unclear.

Another instance in which a S/H circuit can have trouble is when its output is connected to a multiplexer, for example, when multiple S/H circuits drive a single ADC to achieve simultaneous sampling of many channels of dynamic analog data. If the multiplexer, which had been at a voltage of, say, 10V, suddenly connects to the output of a S/H circuit whose output is at −10V, the circuit's output will twitch and then jump to a false level because the multiplexer will couple a little charge into the hold capacitor. The industry-standard LF398 is fairly good at driving multiplexers, but if you get a big enough capacitor and it's charged to a voltage 20V away from the S/H circuit's output voltage, even the LF398's output can jump. I don't have a real solution for this problem, but if you are aware that it can happen, at least you won't tear out all your hair trying to guess the cause. You will recognize the problem,

*Any ADC system is nontrivial and should be engineered by actually plugging in some converter circuits. "Paper designs" usually don't hold water in ADC systems.*

and *then* tear out your hair. About all you can do is try to minimize the capacitance on the output of the multiplexer. One way to do this is by using a hierarchical connection of submultiplexers.

**No agreement on acquisition time's meaning**

Another area of S/H-circuit confusion is acquisition time. I have seen at least one data sheet that defined acquisition time as the time required to go from hold to sample and for the output to settle to a value corresponding to a new value of $V_{IN}$ in the sample mode. However, the outputs of many S/H circuits can settle to a new dc value faster than the hold capacitor charges to the correct value. To avoid confusion, I define acquisition time as the pulse width required for precise sample-and-hold action. If the circuit samples and settles and then goes into hold and gives you the wrong answer, the sample pulse should have been wider.

There may be some S/H circuits whose output voltage won't change if you switch them to the hold mode as soon as their output reaches a value that corresponds to a new $V_{IN}$. But if I had an analog switch that couldn't hold at all, I could still get it to "acquire" a signal according to the data-sheet definition just cited. I consider the test implied by that definition to be too easy. I believe some users and manufacturers in this field agree with my definition, but the situation isn't really clear. (I would appreciate reader comments. You folks are getting all sorts of good ideas from me, and if you have some good comments, it's only fair that you bounce them off me.)

**E pluribus unum: the multiplexer**

Another type of circuit that depends on analog switches is the analog multiplexer. As mentioned already, a multiplexer can draw big transients if you suddenly connect it across big signals at low impedances. So be careful not to overdo operating a multiplexer in this manner, as excessive current could flow and cause damage. It's well known that multiplexers, like most other forms of analog switches, are imperfect due to leakages, on-resistance, and response time. But they are popular and won't give you much trouble until you turn the power bus off and keep the signals going. I recall that in the past few years, at least one or two manufacturers have brought out new designs that could survive some fairly tough overvoltages with the power removed. I'm not sure what the designs involved other than adding thin-film resistors and diode clamps on the inputs—ahead of the FET switches. But if you add discrete resistors ahead of a multiplexer's inputs, the resistors can help the multiplexer survive the loss of power.

One other problem with multiplexers is that you don't have a whole lot of control over the break-before-make margin. And if you should want make-before-break action, I don't think it's an available option. So, sometimes you may have to "roll your own" multiplexer.

If your signal levels are less than 15V p-p, you may be able to use the popular CD4051 and CD4053 multiplexers and the CD4066 CMOS analog switches, which are inexpensive and quick and usually exhibit low leakage. However, if you need a guarantee of very low leakage, you may have to test and select the devices yourself.

So, we take leave of the analog/digital world—sort of. Next time, we'll visit another area of great importance to analog/digital electronics, but it *is* a purely linear region, perhaps the *most* purely linear: references. Armed with knowledge about references, we'll move on to the troubleshooting of power electronics, including switching regulators. EDN

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## Author's biography

*For more information on Bob Pease, see the* ***box,*** *"Who is Bob Pease, anyway," on page 148 of the January 5, 1989, edition of EDN.*


Article Interest Quotient (Circle One)
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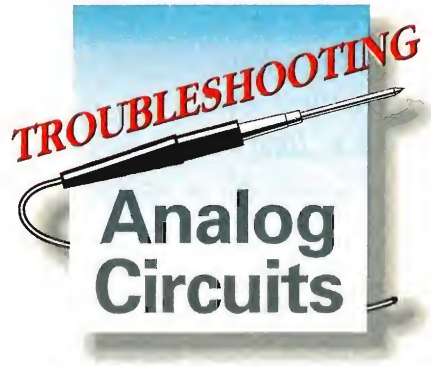



**PART 11**

# Preside over power components with design expertise

*Bob Pease—the self-appointed Czar of Band Gaps—continues his series with words of wisdom on voltage references, regulators, and start-up circuits. He also warns against assumptions about worse-case conditions and discusses the usefulness of Kelvin connections. Next time, Bob wraps up this series with some final remarks about troubleshooting.*

Robert A Pease, *National Semiconductor Corp*

Voltage references and regulators have internal features that make them somewhat immune to problems. But, as with other designs, if you ignore the details, you'll be headed for Trouble. Some designs incorporating these parts, such as switching power supplies, are not for the novice.

Many voltage references are based on band-gap circuitry, but some of the best references are based on buried zener diodes. If your power supply's output is in the 8 to 12V range, zener-diode references can provide high stability, low noise, and a high temperature coefficient. If your power-supply output is a lower voltage, you can find band-gap references that put out anywhere from 0.2 to 5V with creditable efficiency and economy. These band-gap references feature as high a temperature coefficient as you'd probably ever be willing to pay for. But they also feature enough noise so that a little filtering makes a big improvement.

A good buried-zener-diode voltage reference is inherently more stable over the long term than is a band-gap one—zener designs change only 5 to 10 ppm per month. However, if you want the highest stability possible, it's only fair to age, stabilize, and burn-in zener-diode devices first. Also, you must screen out the ones that just keep "walking" away from their set points 10 to 20 ppm every week—there are always a few "sports" that are driftier than the rest. Unfortunately, there's no quick and easy test to distinguish between the drifty ones and the stable ones, except for taking measurements for many hundreds of hours.

### Regulators are *almost* foolproof

In the last 10 years, IC voltage regulators have gotten pretty user friendly. Many people use them with no problems at all. Still, my colleagues and I get at least one call every month about a regulator working poorly. The indignant caller complains, "It's getting hot." We ask, "How big is your heat sink?" The indignant voice responds, "What do you mean, heat sink?" I credit all of you readers with enough smarts to recognize that you can't put a whole lot of power into a little regulator unless you secure it to a sufficient heat sink or fins. Then, there really aren't too many things that are likely to go wrong because voltage regulators have

*Once you realize that you can't put a whole lot of power into a little regulator unless you secure it to a heat sink, not much is likely to go wrong.*

just about every feature for protection against the world's assaults.

You'll have problems with regulators when you don't provide the proper output filtering. Most negative regulators and some other types, such as low dropout regulators, require an electrolytic bypass capacitor from the output to ground. If you insert a tantalum capacitor, you may be able to get away with a value of 1 or 2 μF; if you use an aluminum electrolytic capacitor, you can get away with 20 to 100 μF. But in all cases, an electrolytic capacitor WILL work, and a film or ceramic capacitor WON'T work—its series resistance is just too small. If you put a 1Ω resistor in series with a 1-μF ceramic capacitor, the filtering will be adequate at room temperature, but at −40 or +100°C, the capacitor's value will shrink badly.

Another regulator problem can occur when you add an external transistor to increase the output current. Since this transistor adds gain at dc, it's not surprising that you have to add a bigger filter capacitor on the regulator's output to prevent oscillation. Some of the applications in National Semiconductor data sheets recommend specific values for the filter capacitor, but some of these circuits are quite old. When customers find out that 2N3234s are no longer available, they're likely to substitute a more modern transistor that has a faster response and is likely to oscillate. In this case,

Photographs by Peggi Willis

***When you're "Czar of Band Gaps,"*** *people look up to you.*

## What is worst case?

Once I designed a circuit to drive a 200Ω load at the far end of a 2000-ft RG174U cable. The specifications called for me to test the circuit by driving the near end of the coaxial cable with a low-impedance square wave. I called the engineer who wrote the spec and recommended that we perform the test with about a 39Ω source impedance to avoid bad ringing and reflections along the unterminated cable. He told me that this impedance wasn't necessary; he had already checked out the worst-case conditions with no cable and with 2000 ft of cable. I asked him if he had checked it with 250 ft of cable. Why no, he said. So I suggested he try that.

Shortly thereafter, he called me and agreed that the reflections with 250 ft of cable were intolerable without at least some nominal value of resistance at the source. He had incorrectly assumed that the worst case occurred with the longest cable. It's true that the attenuation was worst with the long length of lossy RG174U cable. But it was this attenuation that caused the ringing and reflections to appear damped out. With the shorter cable, a worst-case condition existed at a place he hadn't expected to find it.

So, be cautious about where you look for worst-case conditions. An op amp may exhibit its worst performance at an output voltage other than its maximum negative or positive swing—or even other than zero volts or zero output current. A regulator's worst-case operating conditions may not be at its full-rated load current. When a regulator's power source is resistive, the power dissipation may be higher at three-quarters of its rated current than at full current.

Once I worked on a regulator

a customer might complain about the dc output's "bad stability" as the regulator is forced into and out of oscillation. (Whoever said you don't need an oscilloscope to check out dc problems?) When these customers ask for help, I not only explain how to stop the oscillation, but I give them Pease's Principle (see the **box**, "Pease's Principle," on page 138 of the September 1, 1989, issue of EDN).

**Too much voltage leads to regulator death**

You CAN kill any regulator with excessive voltage. So if you're driving inductive loads or your circuit has an inductive source, make sure to have a place for the current to go when the normal load path changes. For example, if you're using the LM350 as a battery charger with only a few microfarads on the input, a short between the output and ground is disastrous. When the regulator tries to draw an increasing amount of current from the transformer and then goes into current limit, you can get marvelous 80V transients, which destroy the LM350. The solution is to put 1000 μF—rather than just 1 or 10 μF—across the input.

Users get accustomed to seeing regulators with output noise of about 0.003% of the rated dc output. They get indignant when the noise doubles or triples due to 1/f or popcorn noise. The chances of finding a noisy regulator are quite small, so when some noisy ones DO show up, it's a shock. Unfortunately, no high-volume manufacturer of regulators is in a position to test for those low noise levels or guarantee that you'll never see a noisy part. Please don't expect the manufacturer to admit the parts are bad or unreliable or worthy of being replaced. If you DO depend on super-quiet ICs, it's wise to keep a spare stock of selected and tested parts in a safe. Then, you can find them when the ones you just bought end up being a little too noisy.

These simple tips aren't meant to overshadow the truly difficult areas of regulator design. You might wonder if it's possible for a smart, experienced engineer to design a switch-mode regulator that works well after only minor redesigns and goes into production without a major yield loss. My answer is, just barely. The weasel word here is "smart." If the engineer forgets some little detail and doesn't have a contingency plan to test for it, screen it, or repair the regulators that don't work, then maybe he or she isn't very "smart." Those of us who don't design switchers all the time would have a very poor batting average at getting a design to work right off the drawing board—even if we're really good at designing other circuits. After all, a switcher is a complicated system composed of power transistors, transformers, inductors, one or more control ICs, and lots of other passive components. And, the circuit's layout is critical. The

that ran okay at −55°C, at room temperature, and at +125°C, but not at some intermediate temperatures. That was a nasty one. Because some engineers had tested the regulators at hot and cold temperatures and saw no trouble at these extremes, I had to work very hard to convince them not to ship these parts. I had to take them by the hand and show them where the trouble was. It's like a dumb cartoon I once saw showing three men walking out of a movie—an old man, a young man, and a middle-aged man. The posters said the movie was "fun for young and old." And sure enough, the old man and the young man were smiling, but the middle-aged man was frowning. Even a dumb cartoon can be instructive if it reminds you that bad news is not only where you first expect it. It may be lurking in other places, too.

This story reminds me of a boss who asked me if my new regulator design was really short-circuit proof. I told him, yes, I had tested it with short bursts and long pulses and everything in between for days and weeks. With a wry smile, he went over to a tool cabinet and removed a really big, heavy file. He applied this file with rough, uneven scraping motions to ground and to the output of my regulator. He got showers of sparks out of the regulator, but he couldn't kill it. Then he explained to me that the random, repetitive action of a file sets up patterns of current loads and thermal stresses that can kill a regulator if its short-circuit protection is marginal. There are many, many tricks you can use to show that a design really can survive every worst-case condition.

*Many regulators require electrolytic capacitors on their outputs; ceramic ones simply don't do the job.*

layout must guard electrostatic signals and, even more importantly, electromagnetic strays. The paths for high currents are important, and the paths for cooling air are even more critical.

So when someone asks me how to design a switcher, I ask, "How many do you plan to build?" If the answer is a few dozen and the design is a full-featured high-power job, I encourage the engineer to buy an existing design. But if large volumes are involved, an engineer usually has the time to do the design right and spread that effort over a few thousand circuits.

An alternative to designing your own switcher is using one of a number of small but complete switching-regulator ICs. Some of these chips are about as foolproof—for a switcher—as you can get. You may need a couple resistors, a few capacitors, an inductor, and a fast rectifier, and then it's done. You'll have a cookbook circuit that really does work. If you only need to supply a few hundred milliamps to your circuit, you may not even need a power transistor or a heat sink.

## Kelvin connections improve measurement accuracy

The usefulness of Kelvin contacts and connections is not widely appreciated. In fact, when I received a question about them recently, I found very little printed reference material on the subject. I looked in a few dozen reference books and text books and didn't find a definition or explanation anywhere. I did find some "Kelvin clips," which facilitate Kelvin connections, in a Keithley catalog. I also found some Textool socket data sheets, which mentioned, in a matter-of-fact way, the advantages of Kelvin contacts. I'll try to explain their usefulness in more detail here.

Perhaps the most common use of Kelvin connections is the remote-sense technique. Kelvin connections and sockets let you bring a precise voltage right to the terminal or pin of your circuit under test. If you don't control the supply voltage precisely, you might start failing parts that are actually meeting their specs.

For example, let's say we want to test the load regulation of the

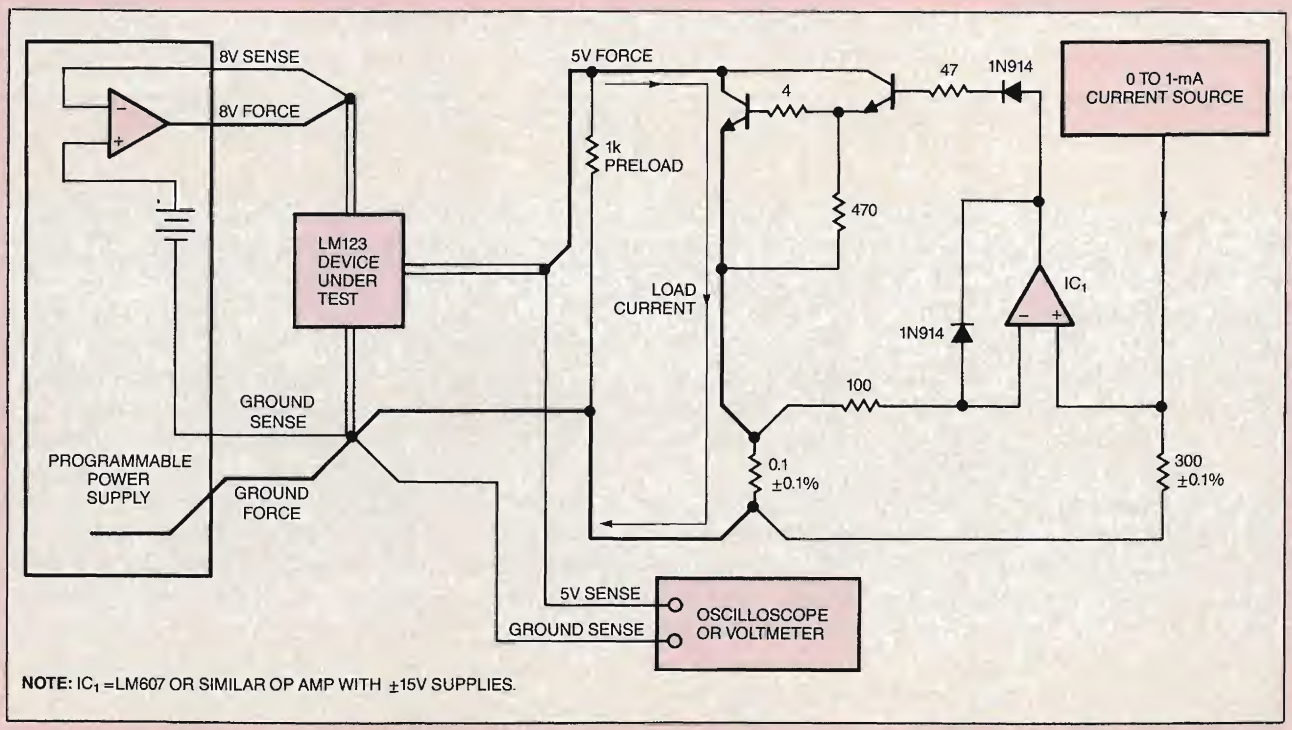



***Fig A—By using Kelvin connections*** *you can avoid measurement errors caused by IR drops in the circuits that you're trying to measure. In this circuit diagram, there are four pairs of Kelvin connections.*

Even in the last couple years there have been advances in designs that really do work, as opposed to paper designs that have no chance of surviving a short on the output or of working under worst-case conditions. Although a few of these useless paper designs still pop up from time to time, thank heaven that most of them have been driven out.

One of the stories that keeps rattling around the industry is about a group of engineers who decide to band together and start a new computer company. The smartest one is assigned to do the main processor board. Another smart engineer does all the interfaces. And the smart but green "kid engineer" is assigned to do the switch-mode power supply because, of course, that's the easiest part to do. (Anybody who has worked on a big switcher will probably speak up right away: The switcher is NOT as easy as it seems.) In the end, the power-supply design takes a lot longer than everybody expects.

One day, the young engineer opens up the compart-

LM323, a 5V regulator, when $V_{IN}=8V$ and the load changes from 5 mA to 3A (**Fig A**). In this circuit, there are four pairs of Kelvin connections shown. The first pair is located at the power supply's output. This programmable supply's remote-sense terminals permit it to maintain an accurate 8V output right up to the pin of the device under test (DUT).

The second Kelvin connection in **Fig A** is located at the output of the DUT. In order for you to observe the changes in $V_{OUT}$ as you apply various loads, the Kelvin contacts provide force leads for the 3A of output current. They also provide sense leads, so you can observe the DUT's output with a high-impedance voltmeter. Note that there are two sense and two force connections to the ground pin of the DUT. You don't really need all four contacts—you can tie both force leads and both sense leads together.

The op amp in **Fig A** forces the DUT's output current through the Darlington transistor and then through a 0.1Ω precision resistor. The only way to use a 0.1Ω resistor with any reasonable accuracy and repeatability is to use the 4-wire connections as shown. The op amp can force the upper sense lead to be precisely 300 mV above the lower sense level, even if the lower end of the resistor does rise above ground due to various IR drops in wires or connectors.

There are several places in this circuit that we could call ground, but the only ground we can connect to the 300Ω resistor and get good results with is the sense lead at the bottom of the 0.1Ω resistor. If you connect the bottom of the 300Ω resistor to any other "ground," shifts in the IR drops would cause relatively large and unpredictable shifts in the value of the 3A current—in other words, Trouble. So, when you're running large currents through circuits, think about the effects of IR drops in various connectors and cables. If you think IR drops will cause trouble, maybe Kelvin connections can get you out of it.

**Fig A**'s fourth Kelvin connection is hidden inside the 5V regulator, which has separate force and sense connections to the output terminal. A fifth Kelvin connection is also concealed inside the current-limit circuitry of the regulator. Here, the device senses current with a 4-wire, Kelvin-connected resistor before the current goes to the current-limit sense amplifier.

The use of Kelvin sockets is not confined to large power transistors or high-current circuits. Consider a voltage reference with 2 mA of quiescent current. If you're trying to observe a 1-ppm stable reference and the ground connection changes by 5 mΩ (which most socket manufacturers do not consider disastrous), the 10-μV shift that results from this change in ground impedance could confound your measurements. If you want to avoid trouble in precision measurements, avoid sockets or at least avoid sockets that do not have Kelvin contacts. Lord Kelvin—William Thomson Kelvin before he was appointed a baron—did indeed leave us with a bag full of useful tools.

*It's just barely possible for an experienced engineer to design a switching regulator that works well the first time out.*

ment where the power supply resides, and it blows up in his face. After his coworkers take the poor fellow to the hospital, they ask around and find a consulting engineer who makes a living out of fixing exactly this kind of switcher problem. The switcher design was slightly off-course and needed the hand of an expert before it would work correctly. So remember, designing switchers is no simple task. Don't hesitate to call in an expert.

**Regulators suit different power levels**

There are several different configurations of switch-mode regulators. At low power levels, capacitively coupled switcher designs are simpler but don't provide much choice of $V_{OUT}$: $1.9 \times V_{IN}$, $-0.9 \times V_{IN}$, and $0.45 \times V_{IN}$ are almost the only choices. Flyback regulators are the simplest and cheapest magnetically coupled regulators. However, at power levels above 100W, their disadvantages become objectionable, and forward or push-pull schemes are more popular. At the highest power levels, bridge-type designs are best. If you try to use a configuration at an inappropriate power level, you may have to struggle to get it working. Likewise, the use of current-mode regulation may help you get faster loop response, but the concept is difficult to understand, let alone execute.

Current limiting is always a problem with switchers. The choice of a sense resistor is not easy because the resistor must have low inductance. As with most aspects of switch-mode regulation, to achieve marginal reliability and to avoid trouble, you have to spend the time to design and test the current-limiting circuit carefully.

Similarly, a soft-start circuit is important for a large switcher, especially when the switcher strains to put out a lot of current to quickly charge up the output filter capacitors. For a large supply, this current could damage transistors, wires, fuses, and power companies. A soft-start circuit forces the switcher to bring the output up to its working levels gradually. I could show you a good soft-start design, but I'll do better than that—I'll show you a bad one. The LM3524 data sheet shows the circuit in **Fig 1** for a 15V, 0.5A step-up switching regulator. (I should mention that this circuit and the LM3524 data sheet were mistakenly left out of National Senmiconductor's 1986 data book. We plan to reinsert them in future editions.)

A step-up switcher needs a soft-start circuit to pre-

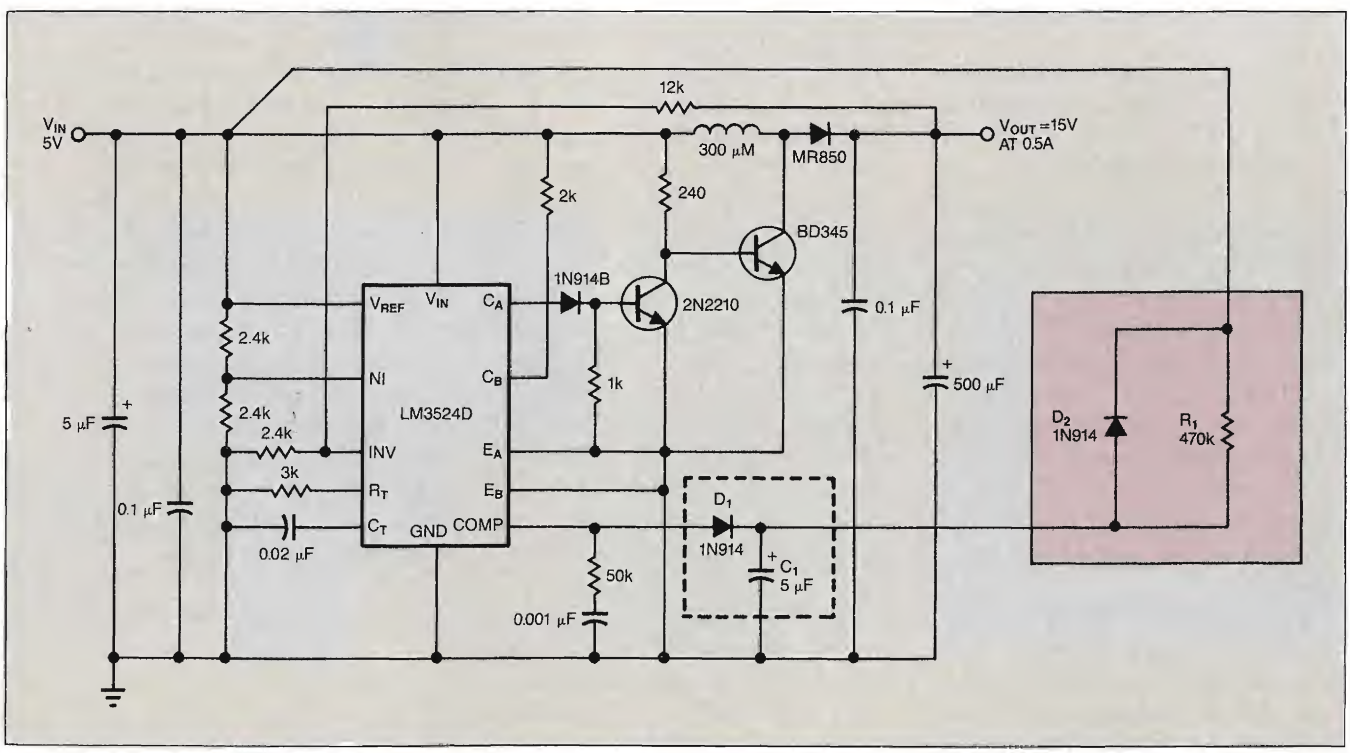



***Fig 1—The addition** of $R_1$ and $D_2$ to this standard data-book design of a 15V, 0.5A switching regulator provides the circuit with better soft-start and restart capabilities.*

*Anyone who has ever worked on a large switching regulator will tell you that designing them is no trivial task.*

vent it from saturating its transformer and from just sitting there at start-up. For this reason, $C_1$ and $D_1$ were included in **Fig 1**'s circuit. But **Fig 1** is still a bad circuit. Let's say that the regulator is running at a low duty cycle and the voltage on the COMP pin is relatively low. Now, as the input voltage changes, the duty cycle may have to increase. But the control amplifier that drives the COMP pin not only has to pull up the series RC network at the COMP pin, but it must also pull $C_1$ up to the new voltage level. This load is too much for the COMP pin's control amp. It's possible to avoid this problem by adding a 470-kΩ resistor from the top of $C_1$ to the input supply. This resistor pulls $C_1$ up to a high level, where it cannot interfere with operation after start-up.

Even after you add the resistor, this circuit is in trouble—especially if the input power shuts off briefly. It takes many seconds to discharge $C_1$, a 5-μF capacitor, and after a brief power outage no soft-start capability will be available. A good fix is to install a diode across the 470-kΩ resistor to discharge $C_1$ quickly when the input voltage drops. This gives you a chance for soft start on the restart. I'm not saying that this circuit is a good worst-case design—you'd have to prove that with engineering and tests. Meanwhile, we'll have to add these components to our LM3524 data sheet.

### Toys illustrate some basics

My first encounter with a start-up circuit happened at a pretty young age. I remember the old toy that resided in a box with a big ON-OFF toggle switch on its front. When your curiosity led you to flip the switch ON, a motor would begin to whir, the top of the box would rise up, and a mechanical hand would reach out. The hand would throw the switch to the OFF position and then retreat back into the box. The cover would close, and the whirring would cease. What a charming way to represent a start-up (or, in this case, a shut-down) function. When I was a kid, I was really impressed by this toy, but later I realized that this logical sequencer was an illusion. The ON-OFF switch DID trigger some kind of a latch to turn the power ON, but it did not directly provide the OFF function. If it did, the hand would stall immediately after it turned the switch OFF and would never continue back inside the box. There was a switch to turn the power OFF, but it was functionally inside the box at the end of the travel of the hand.

The point of the story is that we must make sure not to fool anybody with the start-up circuits we design. When I design an A/D converter, I include a shift-register sequencer to make sure that every necessary task is completed sequentially at the start of conversion and again at the end. I have no idea how software engineers write valid programs to make sure no false start-up sequences occur, but I bet some people do it wrong. Some designs still implement the microprocessor reset function with such crude RC timers that the processor gets confused and doesn't start correctly. I've heard about those horror stories. Sometimes people forget to add the diode to discharge the capacitor, and then the reset fails to work after a brief power outage.

Designers also include start-up circuits in linear circuits. For example, current-bias circuits ensure that a small but stable bias current starts the whole circuit going. Then when the start-up circuit is operating

***Right makes might*** *when you're the Czar of Band Gaps. Overseeing the designs of band-gap voltage references is a brutal job, but somebody has to do it.*

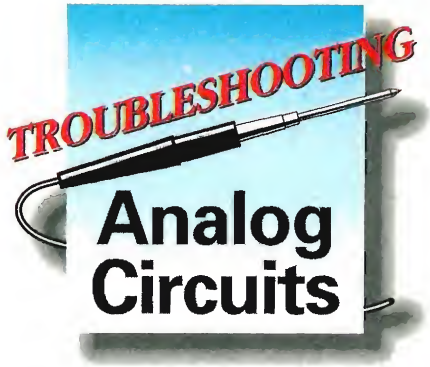
properly, another circuit (a hand) reaches around and shuts off the start-up circuit. When the start-up circuit works properly, it saves power and doesn't waste much die area. Unfortunately, if the start-up circuit is broken or inoperative, the main circuit may still start if the supply voltage jumps up rapidly but may fail to start if the supply ramps up slowly. Once a customer returned a regulator complaining that the device would start if the supply ramped to 20V in 30 seconds, but not if it ramped in 36 seconds. We checked it out, and the customer was absolutely right. We had to change one mask and add a start-up test.

Sixteen years ago, an IC maker designed a micropower IC that didn't have a true dc start-up circuit. The IC was supposed to start up at the transient rise rate of the supply voltage. At room temperature, the circuit would always start, no matter how slowly the supply ramped up. But at cold temperatures, the device wouldn't start even with supplies of ±15V. Worse yet, if the device was running and you hit one of the power supply buses with certain positive or negative transients in sequence, you could turn the part OFF. Needless to say, that part never became popular, nor did anything else from that company.

So, let me caution you: Whether your circuit is a loop of sequential logic or an analog loop with positive and negative feedback, be sure to design it carefully. Add a test to make sure a bad part will be rejected, AND build up a few bad parts and make sure they fail the test. Then leave the test in the flow. Don't drop the test just because nobody has ever seen a part fail. Dropping that test would be courting disaster. Here at National Semiconductor, we've appointed a Czar of Start-up Circuits. He is the repository of all knowledge about circuits that do (and don't) start properly. Since this shy fellow (I shan't give his name) began to reign, the goof-up rate has been cut by many decibels. EDN

## Author's biography

*For information about Bob Pease, see the* ***box,*** *"Who is Bob Pease, anyway?" on page 148 of the January 5, 1989, edition of EDN.*




PART 12

# Troubleshooting series comes to a close

*In any serious troubleshooting situation, planning what tests are most likely to give you the answer quickly, rather than charging off in random directions, is usually wise. Intermittents are the toughest, most frustrating kind of troubleshooting problem. And bench instruments augment an engineer's senses and open the window of perception to the circuits he or she is troubleshooting.*

Robert A Pease, *National Semiconductor Corp*

"Floobydust" is an old expression around our lab that means potpourri, catch-all, or miscellaneous. In this last installment, I'll throw into the floobydust category a collection of philosophical items, such as advice about planning your troubleshooting, and practical hints about computers and instruments.

**Troubleshooting intermittent problems**

The car that refuses to malfunction when you take it to the shop, the circuit that refuses to fail when you're looking at it—does it really fail *only* at 2 am?—these are the problems that require the most extreme efforts to solve.

The following techniques apply to intermittent problems:

1. Look for correlation of the problem with *something*. Does it correlate with the time of day? The line voltage? The phase of the moon? (Don't laugh.)

2. Get extra observers to help see what else may correlate with the problem. This extra help includes both *more people* to help you observe and *more equipment* to monitor more channels of information.

3. Try to make something happen. Applying heat or cold may give you a clue. Adding some vibration or mechanical shock could cause a marginal connection to open permanently.

4. Set up a storage scope or a similar data-acquisition system to trap and save the situation at the instant of the failure. Depending on the nature of the instrument, you may be able to store the data before the event's trigger or after or both.

5. Get one or more buddies to help you analyze the situation. Friends can help propose a failure mode, a scenario, or a new test that may give a clue.

6. As the problem may be *extremely* difficult, use *extreme* measures to spot it. Beg or borrow special equipment. Make duplicates of the circuit or equipment that is failing in hopes of finding more examples of the failure. In some cases, you are justified in slightly abusing the equipment in hopes of turning the intermittent problem into an all-the-time problem, which is often easier to solve.

In case you haven't guessed, I'm not a big fan of *digital* computers. When a computer tries to simulate an analog circuit, *sometimes* it does a good job; but when it doesn't, things get very sticky. Part of the

*Intermittent problems require the most extreme efforts to solve.*

problem is that some people put excessive confidence and belief in *anything* a computer says. Fortunately, my bosses are very skeptical people, and they agree that we must be cautious when a computer makes outrageous promises. Still, we all agree that computers promise some real advantages, if only we can overcome their adversities and problems.

In many cases, if you have trouble with the simulation of an analog system, you troubleshoot the simulation just as you would the circuit itself. You get voltage maps at various "times" and "temperatures," you insert various stimuli, watch to see what's happening, and modify or tweak the circuit just like a "real" circuit. But, just like the Mario brothers, you can encounter problems in Computerland:

1. You might have a bad circuit.
2. You might forget to ask the computer the right question.
3. You might have mistyped a value or instruction or something. The easiest mistake of this sort is to try to add a 3.3M resistor into your circuit. Spice thinks you mean 3.3 *milliohms*, not megohms. This problem has hooked almost everybody I know. I solved it by using "3300K" (3300 kΩ in Spice).
4. You might have a bad "model" for a transistor or device. I've seen a typographical error in the program listing of a transistor's model tie a project in knots for *months*.
5. You might have neglected to include strays such as substrate capacitance, pc-board capacitance, or—something that most people forget—lead inductance.
6. You might get a failure to converge or an excessive run time. Or the computer might balk because the program is taking too many iterations.

Sometimes problems happen that only a computer expert can address. But when you ask the computer guru for advice, you could get no advice or—what's worse—bad advice. After all, many computer wizards know nothing whatsoever about linear circuits. If the wizard tells me, "Hey, don't worry about that," or, "Just change the voltage resolution from 0.1 mV to 10 mV," then I must explain to the wizard that, although that advice might make some computers happy, it gives me results that are completely useless. Talking to computer wizards is sometimes difficult.

Even if you do everything right, the computer can lie to you. Then you have to make a test to prove that *you* can get the right answer and the computer can't. Then, just tell your boss that the computer has proved itself incompetent.

Photographs by Peggi Willis

***Intermittent failures**—especially those that occur only at 2 am—are the toughest to troubleshoot.*

What I really think you ought to do instead of using digital simulations is to make an analog-computer model—you'll have a lot less trouble. Be sure to scale all the capacitances at 100× or 1000× normal, so the time scale is scaled down by 100×, which makes the strays negligible. That's what I do. I will listen to alternative points of view but, be forewarned, with frosty skepticism.

**There's nothing like an analog meter**

Everybody *knows* that analog meters aren't as accurate as digital meters. Except . . . you can buy DVMs with a 0.8% accuracy; analog meters better than that exist. Anyway, let's detail some problems with analog meters.

Even if an analog meter is accurately calibrated at full scale, it may be less accurate at smaller signals because of nonlinearity arising from the meter's inherent imperfections in its magnetic "circuits." You can beat that problem by making your own scale to correct for those nonlinearities. Then there's the problem of friction. The better meters have a "taut-band" suspension, which has negligible friction—but most cheap meters don't. Now, as we have all learned, you can neutralize most of the effects of friction by gently rapping on, tapping at, or vibrating the meter. It's a pain in the neck, but when you're desperate, it's good to know.

Even if you don't shake, rattle, or roll your meters, you should be aware that they are position-sensitive and can give a different reading if flat or upright or turned sideways.

The worst part about analog meters is that if you drop them, any of these imperfections may greatly increase until the meter is nearly useless or dead. This

is "position sensitivity" carried to an extreme. Ideally, you would use digital meters for every purpose. But analog meters have advantages when, for example, you have to look at a trend or watch for a derivative or an amplitude peak—especially in the presence of noise, which may clutter up the readings of a digital voltmeter. So, analog meters will be with us for a long time, especially in view of their need for no extra power supply, their isolation, and their low cost.

But, beware of the impedance of meter movements. They look like a stalled motor—a few hundred millihenries—at high frequencies. But if the needle starts swinging, you'll get an inductive kick of many henries. So, if you put an analog meter in the feedback path

## Methodical, logical plans ease troubleshooting

Even a simple problem with a resistive divider offers an opportunity to concoct an intelligent troubleshooting plan. Suppose you had a series string of 128 1-kΩ resistors. If you applied 5V to the top of the string and 0V to the bottom, you would expect the midpoint of the string to be at 2.5V. If it weren't 2.5V but actually 0V, you *could* start your troubleshooting by checking the voltage on each resistor, working down from the top.

But that strategy would be absurd. Checking the voltage at, say, resistor #96, then at #112 or #80, then at #120 or #104 or #88 or #72—branching along—would be much more effective. With just a few trials, you could find where a resistor was broken open or shorted to ground. Such branching along would take a lot fewer than 64 tests.

Further, if an op-amp circuit's output was pegged, you would normally check the circuit's op amp, resistors, or conductors. You wouldn't normally check the capacitors, *unless* you guessed that a shorted capacitor could cause the output to peg. Conversely, if the op amp's $V_{OUT}$ was a few dozen millivolts in error, you might start checking the resistors for their tolerances. You might not check for an open-circuited or wrong-value capacitor, *unless* you checked the circuit's output with a scope and discovered it oscillating.

So, in any circuit, you must study the data—your "clues"—until they lead you to the final test that reveals the true cause of your problem.

Thus, you should always first formulate a hypothesis and then invent a reasonable test or series of tests, the answers to which will help narrow down the possibilities of what is bad and may, in fact, support your hypothesis. These tests should be performable. But you may define a test and then discover it is *not* performable or would be much too difficult to perform. Then I often think, "Well, if I *could* do that test, the answer would either come up 'good' or 'bad.' OK, so I can't easily run the test. But if I assume that I'd get one or the other of the answers, what would I do next to nail down the solution?"

For example, if I had to probe the first layer of metal on an IC with two layers of metal because I had neglected to bring an important node up to the second metal, I might do several other tests instead. I would do the other tests hoping that maybe I wouldn't have to do that probing, which is rather awkward even if I can "borrow" a laser to cut through all the layers of oxide. If I'm lucky, I may never have to go back and do that "very difficult or nearly impossible" test.

Of course, sometimes the actual result of a test is some completely unbelieveable answer, nothing like the answers I expected. Then I have to reconsider—where were my assumptions wrong? Where was my thinking erroneous? Or, did I take my measurements correctly? Is my technician's data really valid? That's why troubleshooting is such a challenging business—almost never boring.

On the other hand, it would be foolish for you to plan *everything* and test *nothing*. Because if you did that, you would surely plan some procedures that a quick test would show are unnecessary. That's what they call "paralysis by analysis." All things being equal, I would expect the planning and testing to require equal time. If the tests are very complicated and expensive, then the planning should be appropriately comprehensive. If the tests are simple, as in the case of the 128 resistors in series, you could make them up as you go along.

*Some people put excessive confidence in anything a computer says.*

of an op amp, you'll need a moderate feedback capacitor across the meter.

As I mentioned before, digital meters are *always* more accurate than analog meters . . . except for when they aren't. Recently, a manufacturer of power supplies decided to "modernize" its bench-type supplies by replacing the old analog meters with digital meters. Unfortunately, these meters came with an accuracy of ±5%. Having a 2½-digit digital panel meter (DPM) with a resolution of 1 part in 200 but an accuracy of 1 part in 20 certainly is silly. Needless to say, I stopped buying power supplies from that manufacturer.

The steadiness and irrefutability of those glowing, unwavering digits is psychologically hard to rebut. I classify the readings of the DVM or DPM with any other computer's output: You have to learn to trust a computer or instrument when it's telling the truth and to blow the whistle on it when it starts to tell something other than the truth.

For example, most slow DVMs have some kind of dual-slope or integrating conversion, so they're inherently quite linear, perhaps within 1 or 2 least-significant digits. Other DVMs claim to have the advantage of higher conversion speed; this higher speed may be of no use to the bench engineer, but it is usable when the DVM is part of an automated data-acquisition system. These faster instruments usually use a successive-approximation or recirculating-remainder conversion scheme, both of which are not inherently linear but depend on well-trimmed components for linearity. I have seen several DVMs that cost more than $1000 and were prejudiced against certain readings. One didn't like to convert 15 mV; it preferred to indicate 14 or 16.

I hate to use a DVM's autoranging mode. I have seen at least two—otherwise high-performance—DVMs that could not lock out the autorange feature. The worst aspect of these meters was that I couldn't tell where they would autorange from one range to another, so I couldn't tell where to look for their nonlinearity. After an hour of searching, I found a *couple* of missing codes at some such preposterous place as 10.18577V. And this on a $4000 DVM that the manufacturer claimed could not have such an error—could not have more than 1 ppm of nonlinearity.

Another DVM had the ability to display its own guaranteed maximum error, saying that its own error could not be more than ±0.0040% when measuring a 1-MΩ resistor. But then it started indicating that one

***Spice printouts** are almost always good for something.*

of my better 1.000000-MΩ resistors was really 0.99980 MΩ. How could I prove it was lying to me? Easy—I used jiujitsu by employing its own force against itself. I got ten resistors each measuring exactly 100.000 kΩ—all the DVMs in the lab agreed on these resistors' values. When I put all 10 resistors in series, all the other meters in the lab agreed that they added up to 1.00000 MΩ; the fancy but erroneous machine said 0.99980 MΩ. Back to the manufacturer it went.

So, if you get in an argument with a digital meter, don't think that you *must* be wrong. You can usually get an opinion from another instrument to help prove where the truth lies. Don't automatically believe that a piece of "data" must be correct *just* because it's "digital."

And be sure to hold onto the user's manual that comes with the instrument. It can tell you where the guaranteed error band of the DVM gets relatively bad, such as for very low resistances, for very high resistances, and for low ac voltages.

Most digital voltmeters have a very high input impedance (~10,000 MΩ typ) for small signals. However, if you let the DVM autorange, at some level the meter will automatically change to a higher range where the input impedance becomes 10 MΩ. Some DVMs change at 2V or 3V, others at 10 or 12 or 15V, and yet others at ±20V. As I mentioned in the section on equipment, I like to work with the DVMs that stay high-impedance up to at least 15V. But, the important thing is to know the voltage at which the impedance changes. A friend reminded me that a guy he knows had recently taken a week's worth of data that had to be retaken because

*In some cases, you are justified in slightly abusing equipment in the hopes of turning an intermittent problem into an all-the-time problem.*

he neglected to allow for the change of impedance. I think I'll go around our lab and put labels on each DVM.

Still, DVMs are very powerful and useful instruments, often with excellent accuracy and tremendous linearity and resolution—often as good as 1 ppm. I've counted some of these ultralinear meters as my friends for many years. I really do like machines that are inherently, repeatedly linear.

One picky little detail: Even the best DVM is still subject to the adage, "Heat is the enemy of precision." For example, some DVMs have a few extra microvolts of warm-up drift, but *only* when you stand the box on its end or side. Some of them have a few microvolts of thermal wobble and wander when connected to a zero-volt signal (shorted leads), but *only* when you use banana plugs or heavy-gauge (16, 18, or 20 gauge) leads—not when you use fine wire (26 or 28 gauge). The fine-wired leads do not draw as much heat from the front-panel binding posts. So, even the best DVM auto-zero circuit cannot correct for drifts outside its domain.

Most engineers know that DVMs add a resistive (10-MΩ) load to your circuit and a capacitive load (50 to 1000 pF) that may cause your circuit to oscillate. But, what's not as well known is that even the better DVMs may pump noise back through their input terminals and spray a little clock noise around your lab. So if you have a sensitive circuit that seems to be picking up a lot of noise from *somewhere*, turn off your DVM for a few seconds to see if the DVM is the culprit. If that's not it, turn off the function generator or the soldering iron.

## Signal sources

While I'm on the subject of instruments, I really enjoy using a good function generator to put out sines and triangle waves and square waves and pulses. But I certainly don't expect the signals to be undistorted—all these waveforms will distort, especially at high frequencies. So if I want my function generator to give me a clean sine wave, I put its output through an active filter at low frequencies or an LC filter at high frequencies. If I want a clean, crisp square wave, I will put the signal through a clipping amplifier or into a diode-limited attenuator (**Fig 1**). If I want a cleaner triangle than the function generator will give me, I just make a signal generator from scratch.

A function generator lets me down when some absent-minded person pushes one button too many and the output stops. It can take me five minutes to find what the problems are. I love all those powerful versatile functions when I need them, but they drive me nuts when the wrong button gets pushed.

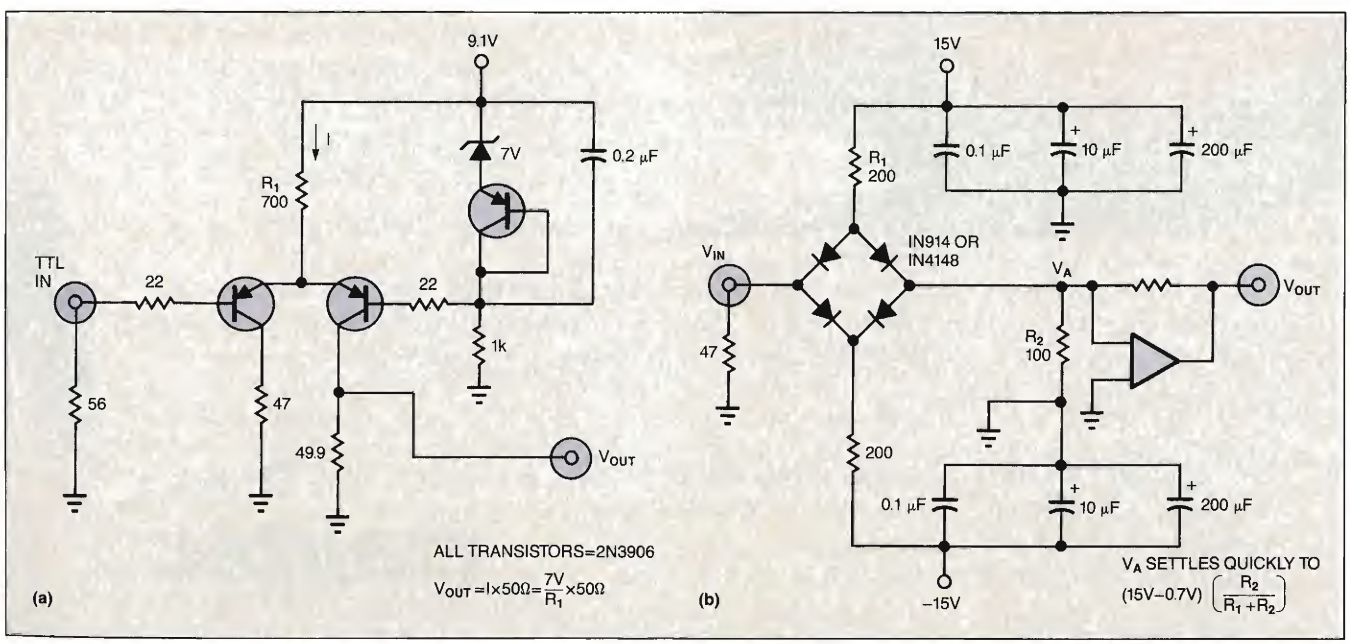



***Fig 1—Either a clipping amplifier (a)*** *or diode-limited bridge* ***(b)*** *will give you a clean, crisp square wave.*

*I've seen a typographical error in the program listing of a transistor's model tie a project in knots for months.*

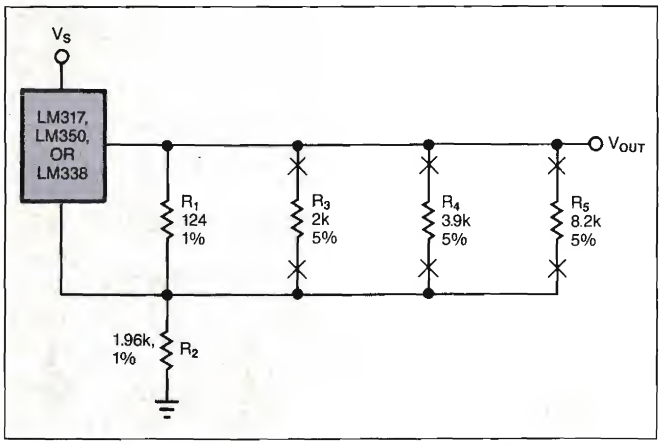



***Fig 2—If you're worried that some foolish person** will ruin a circuit by misadjusting a trimming potentiometer, you can foil the bungler with this "snip-trim" network. The procedure for trimming $V_{OUT}$ to 22V within 1% tolerance is as follows: If $V_{OUT}$ is higher than 23.080V, snip out $R_3$ (if not, don't); then if $V_{OUT}$ is higher than 22.470V, snip out $R_4$ (if not, don't); then if $V_{OUT}$ is higher than 22.160V, snip out $R_5$ (if not, don't). Obviously, you can adapt this scheme to almost any output voltage. Choosing the breakpoints and resistor values is only a little bit tricky.*

Similarly, a scope's trace can get lost and hide in the corner and sulk for many minutes on end if you don't realize that somebody (maybe your very own errant fat finger) pushed a treacherous button. When the digital scopes with their multiple layers of menus and submenus start playing that game, I find I need a buddy system—somebody to come and bail me out when I get hopelessly stuck. What *menu* is that dratted beamfinder on, anyway?

But, scopes work awfully well these days. Just don't expect precision results after you drive the trace many centimeters off scale by turning up the gain to look at the bottom of a tall square wave. Scopes aren't obligated to do that very well. Similarly, be sure to keep the trimmers on your 10× probes well adjusted, and run a short ground path to your probes when you want to look at fast signals.

### How to trim without trimming potentiometers

Speaking of keeping circuits well trimmed, some people like to use trimming potentiometers to get a circuit trimmed "just right." Other people hate to because the potentiometers are expensive or unreliable or drifty. Worst of all, if a circuit can be trimmed, it can also be mistrimmed; some person may absent-mindedly or misguidedly turn the potentiometer to one end of its range or to the wrong setting. How long will it take before that error is corrected?

For just this reason, some people prefer fixed-voltage regulators because they always have a valid output (±5%) and can never get goofed up by a trimming potentiometer. Other people need a tighter tolerance yet are nervous about the trimming potentiometer. You will find the solution in the snip-trim network in **Fig 2.** This scheme will let you trim a regulator well within 1% without trimming potentiometers. Note that you could also use this technique to set the gain of integrators and the offset of amplifiers. It's not always easy to engineer the correct values for these trims, but it is possible. And, nobody's going to go back and *tweak* the potentiometer and cause trouble if there's no potentiometer there to tweak.

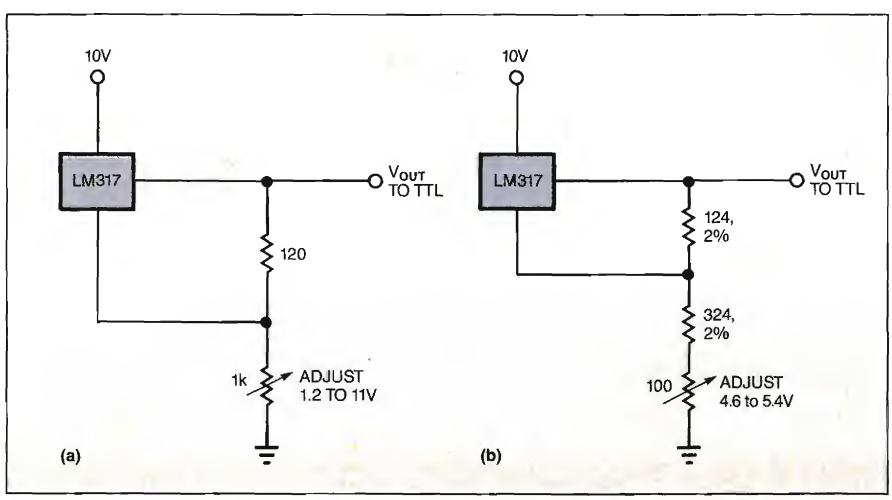



***Fig 3—You can avoid incurring Bob's ire** if you dodge one of his pet peeves: an excessive trimming-potentiometer adjustment range **(a)**. The circuit in **b** suits TTL much better.*

A pet gripe of mine concerns engineers who design a circuit with an adjust range that's so wide that damage can occur. For example, **Fig 3a** is a bad idea for a regulator for a 5V supply for TTL because the TTL parts would be damaged if someone tweaks the pot to one end of its range. **Fig 3b** is better.

In closing, let's all work together lest troubleshooting become a lost art. I've done my bit, now you do yours. Send your own troubleshooting articles to EDN. If you don't have enough troubleshooting ideas to produce a full-length article but do have some good tips that you didn't see in this series, send them to EDN's Design Ideas editor. No doubt, EDN will print some of them. Please send me a copy of anything you send to EDN—I'd love to look at it. And if you've got any comments about *my* series, please write to me at National Semiconductor Corp, M/S C2500, Box 58090, Santa Clara, CA 95052. After all the tips I've given you, it's only fair that you share your comments with me. EDN

## Author's biography

*For more information about Bob Pease, see the* ***box,*** *"Who is Bob Pease, anyway?" on page 148 of the January 5, 1989, edition of EDN.*

## Acknowledgments

*I want to express my appreciation to the 40-odd friends who helped review the drafts of these articles, correct my mistakes, and suggest additions. Special thanks go to Jim Moyer, Tim Regan, Dennis Monticelli, and to Dan Strassberg at EDN, who contributed significant technical ideas that were beyond my experience. Credit goes to Mineo Yamatake for his elegant thermocouple amplifier design, Steve Allen and Peggi Willis for their photography, and Erroll Dietz as Key Grip and Carlos Huerta as Gaffer. And kudos to each of the EDN editors who slaved over my copy: Julie Anne Schofield, Anne Watson Swager, Charles H Small, and Dan Strassberg. I am also grateful to Joyce Gilbert, who wound up typing a lot more than she bargained for. She believed me when I told her it would only be 50 or 60 pages typed . . . how were we to know how this would grow?*

Article Interest Quotient (Circle One)
High 497 Medium 498 Low 499

# Pease's pointers rouse readers:

# Letters to Bob

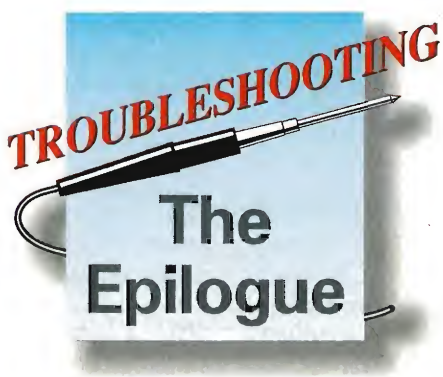
*Bob Pease's series on troubleshooting generated myriad letters from readers—far more than we could do justice to in our Signals and Noise column. Because so many of the letters contained worthwhile troubleshooting tips and amusing personal anecdotes, EDN's editors decided to collect some of the best letters into an article, along with Bob's replies and interjections. (Turn to the last page of this article for a list of the issues that contain the 12-part "Troubleshooting Analog Circuits" series.)*

## The tips just keep on coming

Dear Bob:

Here are some tips and gotchas:

1. A significant source of noise in my lab is the ever-present video-display terminal. It couples especially well to audio-frequency transformers.




2. I head off a lot of trouble by providing RF bypass on audio and dc circuits. Their audio and low-frequency-only inputs can pick up AM radio. Having music come out of a speaker that is supposed to be a monitor on a telephone circuit is very bad form.

3. My computer brethren frequently fail to consider what happens during reset. I saw a thermal printer catch on fire once when its internal μP was reset. The reset 3-stated the print head's drivers, which allowed all of them to turn on continuously. Later a software bug turned them on continuously again. I finally made the print head computer-proof by capacitively coupling the drivers so that the μP had to produce a continuous sequence of pulses to keep the heads turned on.

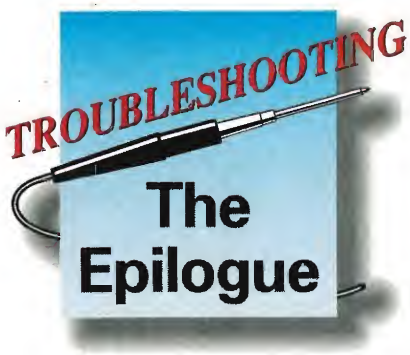
4. My inexperienced brethren frequently forget to calculate total power-supply requirements.

5. Vishay (Malvern, PA) produces some very accurate, very stable (0.6 ppm/°C) resistors, which I keep around to check ohmmeters.

6. Some companies think they are helping designers by taking instruments to the calibration lab without

letting the designers know. They do not understand that small day-to-day drifts are less annoying than an unexpected step change produced by recalibration.

7. My computer brethren frequently lose scope-probe ground clips—the clips get in their way and sometimes short a power supply. I gave up and bought a pile of the clips that I keep in my bench.




8. Sad but true, sometimes adding a scope probe to a malfunctioning circuit makes the circuit work. The probe adds enough capacitance to kill a glitch or stop a race. On floating CMOS, the dc impedance of the scope can be low enough to pull the signal down to a valid level.

9. At one place I worked, I was called to the factory to make my "no-good" circuit work. The complaint was that the dc offset of an op amp was drifting. When I got there, I found the technician had a good DVM connected to the op amp through a piece of coaxial cable to keep out noise. Of course, the cable's capacitance was making the op amp oscillate. You can't measure dc parameters when the op amp is oscillating. Sometimes I find a scope connected this way because the tech wanted more gain or could not find a 10× probe.

10. Probes work into a certain, specified scope-input capacitance. You can't always take a probe that came with one scope and use it at high frequencies on another scope.

11. A simple test technique is waving your hand over a circuit to feel for the hot spot. If something has gone into latch-up but is not smoking, you can frequently find it this way.

12. Edmund Scientific (Barrington, NJ) sells thermally sensitive liquid-crystal sheets, which you can lay over a circuit to find moderate hot spots. This material works well when you have a known-good pc board to compare with the circuit under test.

13. Drafting departments sometimes erroneously think that they own the schematic and that its only purpose is to serve as a wiring diagram for the pc-board layout. Long after pc-board layout, the production-test, sustaining-engineering, and service departments will still need the schematic. Drafting tends to lose notes that I place on the schematic, such as filter poles and zeros, temperature coefficients, normal ac and dc voltages, waveforms, and thermal information. I save myself a lot of calls by putting this information in front of the techs from the beginning.

14. You can make an extremely low-distortion (and slightly microphonic) sine-wave oscillator from a light bulb and an op amp. I got the circuit from Linear Technology's (Milpitas, CA) AN 5 application note. I built a 3-frequency (400-, 1000-, and 2800-Hz) oscillator in a small metal Bud box. It had a THD lower than −80 dB.

15. If a circuit's dc values change when you breath on it, you may have dirty circuit boards.

16. When testing high-gain, low-signal-level circuits, repeat the measurements with the lights off. You may be surprised to learn that many components are photosensitive and have infrared transparent bodies. One of my colleagues had a photosensitive metal-can op amp that leaked light in around the leads.

17. Protection diodes can rectify high-frequency noise and oscillations.

18. Micro Technical Industries (Laguna Hills, CA) makes a handy thermal probe with which you can individually heat components. The probe has tips to fit various components, such as small and large resistors, metal-can op amps, and DIPs of various sizes.

19. Some sample-and-hold circuits are sensitive to slew rates on the digital inputs.

20. Even Schmitt triggers can exhibit metastability.

21. As paraphrased from an Analog Devices (Norwood, MA) application note, "You may be able to trust your mother, but you should never trust your ground."

22. Wrapped-wire circuits work pretty well if you can distribute power and ground properly. I use large-diameter bus wire in a rectangular grid for high-frequency logic if I don't have a wrapped-wire board with internal power and ground distribution.

23. Sometimes powering your test circuit with batteries breaks ground loops and eliminates power-line noise.

24. A handy thing to have is a 60-Hz, passive, twin-T notch filter in a small Pomona box with dual banana plugs for input and output.

25. Another handy thing to have is a 20-dB high-impedance amplifier in another Pomona box. The cir-

cuit in **Fig 1** works at audio frequencies.

**26.** The CMRR of an op amp is not a constant function of the common-mode voltage. This inconsistency often dominates nonlinearity in noninverting circuits.

**27.** Getting some engineers to hold design reviews is hard. By law, our drafting department will not start a pc-board design until the designer hosts a review. The drafting supervisor can easily enforce this policy because he does not report to the first-level engineering managers. The moral indignation of the designer's peers informs the quality of the review.

**28.** Those partial, but detailed schematics National Semiconductor sometimes places on data sheets provide valuable insight into how a part may be acting in unusual circumstances. Please encourage National to continue the practice.

Roy McCammon
3M/Dynatel
Austin, TX

Hello to Mr McCammon:

Well, I thank you for your comments, many of which are excellent. I will comment on some of them individually, but, as a collection, they are the best new ideas that anybody has given me.

**1.** Noise from a video terminal? I have not seen that problem, but such noise may be a serious problem in some cases. I don't have a *digital* computer near my workbench, but other people may. As I mentioned in Part 2 of my series, if you bring an AM radio near a computer or keyboard, the radio will detect various amounts of graunchy RF noises.

**2.** I, too, recommend RF bypassing. But you point out that bypassing should be *against* ambient RF. I rarely think of bypassing in those terms, but you are right.

**6.** I agree that spiriting away equipment for calibration is a serious issue. In our group, we used to have equipment disappear for calibration just when we needed the equipment desperately. We finally resolved the problem by requiring that engineers put their equipment on a calibration shelf when it was due to be calibrated. If they don't put it there, the calibration guys won't steal it.

**7.** Scope probe parts and ground leads do tend to disappear. We have a budget for those items every year, so we avoid running out.

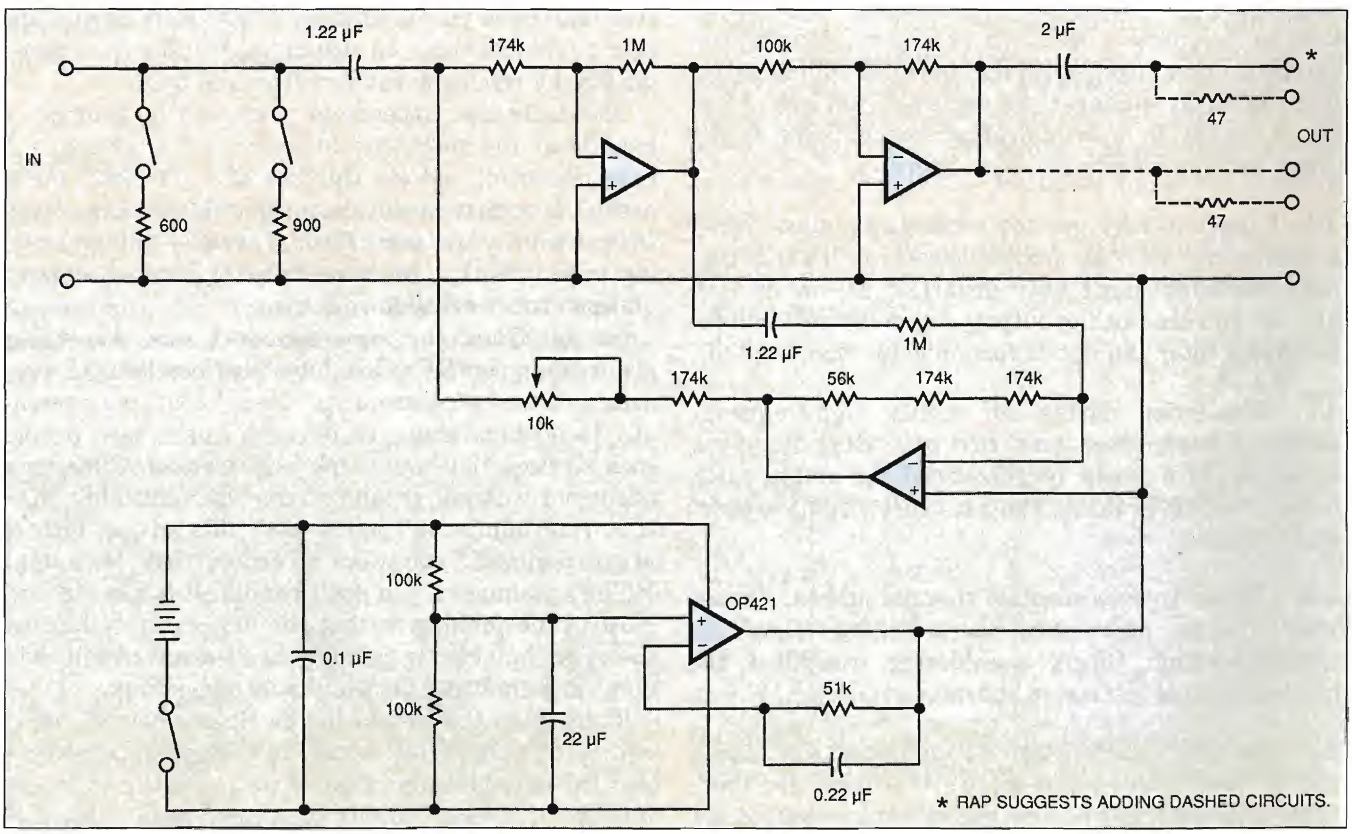



***Fig 1—This 20-dB high-impedance amplifier** works at audio frequencies and is a handy troubleshooting aid.*

9. You are right that adding a chunk of coaxial hose on an op-amp's output can sure make it unhappy, more often than doing so makes it happy. You are right to complain that foolish people pull such stunts. "Show me where it says I can't do it," they protest. *(Ed Note: The Sufis have a saying, "There's no point in putting up signs in the desert saying, 'Thou shalt not eat rocks.' ")*

10. Good statement about probe compatibility. Sometimes you turn the adjustment all the way to the end, and the probe still won't neutralize out.

11. Good point. I often check my soldering iron by running the tip past my nose—about one inch away—to see if it's good and hot. *(Ed Note: Humans have infrared receptors in their lips. If you close your eyes and slowly raise the back of your hand past your lips, you should be able to sense the presence of your hand. Use the back of your hand because the callouses on the palm of your hand block heat radiation.)*

13. You point out that " . . . drafting departments tend to lose notes." Well, where *I* work, drafting departments do a task, and if that includes adding notes, then they add whatever the engineer requires. Actually, I usually do my own draftpersoning. Some people gripe, but the information is all there.

14. I don't usually get too enthusiastic about using incandescent lamps for amplitude control. It's true that most oscillators don't have distortion as low as −80 dB, but you can put the output of a mediocre oscillator through a filter and get distortion lower than −80 dB.

17. "Protection diodes can rectify high-frequency noise." I have never seen this one. Boy, Roy, you must live in a *nasty* neighborhood for ambient RF noises. You can probably run a transistor radio without any batteries.

18. I forgot to even mention thermal probes. We use such probes more for characterizing than for troubleshooting. Often, a soldering iron does the troubleshooting job faster but more crudely.

19. The LF198 data sheet mentions that you should not let the Sample input move too slowly. Are there other S/H circuits that are touchy? Ones that do not mention this fact in their data sheets?

22. I rarely work with wrapped-wire stuff, but I bet a lot of people get fooled by bad daisy-chaining of power-supply runs and lousy power-supply bypassing—whether for linear or digital ICs.

23. I rarely find batteries necessary, but, in extreme cases, they are useful.

24. I rarely find notching out 60- or 120-Hz interference necessary. I usually subtract the 60-Hz noises visually from a scope trace.

27. Design reviews are a good idea. But even if the circuit design is perfect, I find the layout to be pretty critical. So a beer check by all your buddies is awfully important, too.

RAP

## Reader's letter causes change of heart

Dear Bob:

As a practicing technician for many years, I want to comment on one or two things I read in your series and perhaps pass on an experience or two.

On pg 130 of the August 17, 1989, article, you mention the possibly harmful side effects of drawing base current out of a transistor. Most (if not all) of the switched-mode power supplies I have come across appear to do just that—to switch the transistor off more quickly by removing carriers from the base.

This technique appears to work well in practice. I have used the technique in many of the inverters I have designed, and (on the face of it, at least) there doesn't appear to be any component deterioration over time. I usually use some form of reverse-voltage limiting to ensure that the base-collector junction doesn't undergo zener breakdown.

On pg 132 of the same article, I read something about plugging MOS ICs into "live" sockets—I presume you mean "powered up." If so, I could not personally recommend doing so because I have seen people cook devices that way. You also mention something about not wearing ground straps when handling MOS ICs. I certainly can't agree with this advice, either. My experience, and that of others, has been that MTBFs plummet if you don't handle MOS ICs with kid gloves. The problem is that the device rarely fails on the spot, but having possibly been overstressed, will do so at a time and place of its own choosing.

Turning to the article in the September 28, 1989, edition of EDN, I feel bound to present a caution regarding tantalum capacitors. First, they are even less tolerant of reverse polarity than electrolytic capacitors are. Reverse polarity can arise when, say, coupling

op amps with tantalum capacitors. Second, I have replaced more tantalum capacitors than I can remember because they short-circuited for no good reason.

The worst place for a bad tantalum capacitor is on a computer mother board, which is just where I found the last one I replaced. The job started out as a short that was shutting down the power supply. Ascertaining which rail the problem was on was easy enough. I decided that because of the number of components on the bus, I would have to try something less radical than temporarily isolating a section of the rail. I tackled the problem by feeding a 10-kHz sine wave at about 1V rms through a 1-kΩ resistor and monitoring the traces with a current probe. I found the offending component in less than a minute. I may have been lucky, but, on the other hand, my test signal wouldn't cause the ICs to draw any significant current and was of a low-enough frequency not to cause enormous current in the good decoupling capacitors.

In the same article, you said that floating TTL inputs is reasonably OK. In some situations, particularly noisy ones, I would have to disagree. I have seen nasty problems where this practice causes random glitches. The circuit in **Fig 2** is an absolute nightmare. Yet this practice is common on IBM PC clones from Asian manufacturers in, of all things, the glue logic of 80386 mother boards, where high-speed clocks are the norm.

Michael Watts
Wellington Polytechnic
Wellington, New Zealand

Dear Mr Watts:

Thank you for your comments. You question the practice of pulling current out of a transistor's base circuit. If you were to actually pull current out of the base and forward-bias the transistor's intrinsic base-emitter zener, you could cause damage. If, instead, the circuit prevents zener breakdown and its clamps prevent excessive reverse $V_{BE}$, then everything is fine. I probably wasn't clear enough about those points. Note that many discrete transistors are not as fragile—are not going to be damaged or degraded by zener breakdown—as monolithic transistors are. (I'm not sure why.)

Also, you recommend against plugging CMOS components into live (powered-up) circuits and working without a ground strap. You say you have seen such procedures directly cause unreliability and failures. OK, you have and other people have, but I haven't. Perhaps RAM chips are more fragile than 74Cxx chips. So, I must retract my cavalier and flippant remarks: In general, you should use ground straps and not plug ICs into live circuits unless you are *sure* you know what you're doing and are prepared to accept IC failures.

However, when troubleshooting, sometimes you may have to resort to these measures. You should then be aware that they may not necessarily cause harm. But I, and the readers, should be aware that sometimes they may cause harm, so don't hack around if you don't have to.

As for tantalum capacitors, I've seen very few fail with no provocation. I've used a lot of cheap tantalum capacitors, and they must have been more reliable than I deserved. To ensure that they survive reversal, I suggest the arrangement in **Fig 3.**

Using a current probe to find short circuits is a viable technique, but I don't understand how you can clip a current probe around a board trace. I find that my dc microvolt detector, which appeared in Part 2 of the series, will let you track down such dc shorts. If I had to troubleshoot a lot of boards, I'm sure one of your audio-output, milliwatt detectors would be terribly useful.

Although I've never seen a problem with floating TTL gates, you are correct to caution against circuits like the one in **Fig 2.**

RAP

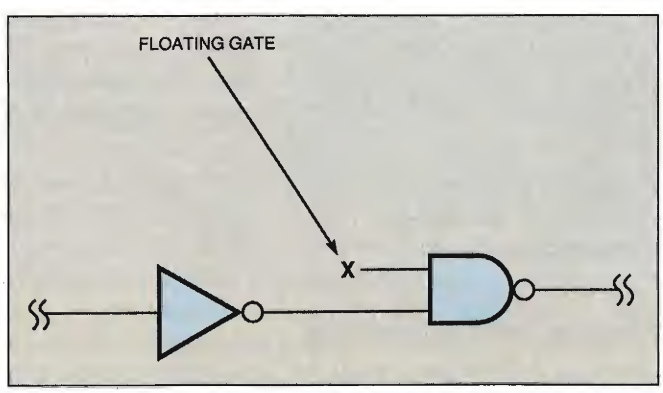



***Fig 2—Letting TTL gates float** is a potentially dangerous practice.*

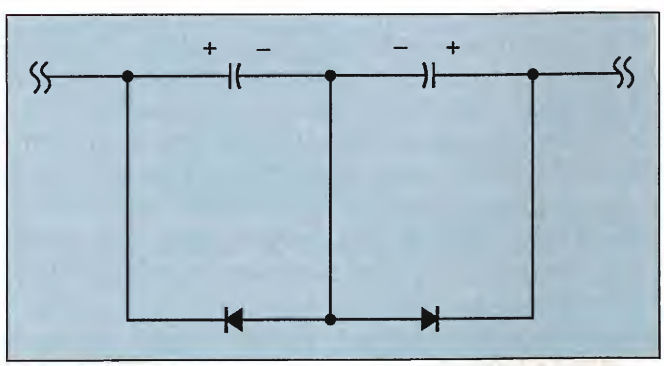



***Fig 3—This scheme will make your tantalum capacitors** immune to damage from reversal.*

## Old hand passes on secret TTL lore

Dear Bob:

As an old hand with 30 years in the business, I have run into some anomalies you did not mention.

1. LS logic is totally unforgiving of negative undershoots at its inputs. The worst chips I have seen are 74LS86s, which hang up for microseconds, totally confusing other circuitry. The second worst is the 74LS75, which can go into either logic state after a negative undershoot but will recover upon the next clock pulse.

2. I have seen circuits with a 7470, -73, -76, -107, -109, -110, or -111 that "remember" highs on the Preset and Reset lines and toggle in spite of a low-high condition at clock time. This anomaly happens if the clock is left high and is not pulsed.

J Koontz
Chief Engineer
Computer Automation
Irvine, CA

## TV chassis tells a tale for all to hear

Dear Bob:

If an engineer wants to see how to properly control EMI at its source, he or she should look at the chassis of any TV and tuner. Chances are, any radiation from internally generated 15-kHz to 950-MHz signals meets FCC Part 15 rules. Obviously, most TV receivers do not depend on their plastic cabinets to contain spurious radiation.

For some time now I have been working with labs that attempt to certify radiating equipment that was not designed using basic radiation-containment methods. These methods date back to the time of tube circuits and include using specialized components such as feedthrough capacitors, ferrite beads, and toroidal coils. These methods also include using very light-gauge, low-cost, tin-plated steel cans to enclose radiating components. Soldering the tabs of these 5-sided cans to the pc board forms a complete 6-sided enclosure around the radiating component. Note that TV receivers' pc boards have considerable ground-plane area.

If you do not design out EMI, someone will have to design in some Band-Aids to fix your bad design.

Here are some points to consider:

1. Incorporate as much ground plane as possible on one side of each pc board that contains digital or analog signals above audio frequencies. Be sure this ground plane has a low-inductance path to the main chassis—even if this path goes through an edge connector.

2. Incorporate a T or L RC filter on all input and output lines. The resistor should always be on the side leading away from the hot circuit. It should be the largest value possible, as great as 1 kΩ. This resistor will damp, or "de-Q," any resonant circuit that the interconnect lines form as well as filter the noise. You must choose the resistor and capacitor carefully so as not to adversely affect the desired signal on the line. The capacitor should be a ceramic disk with a value between 10 pF and 0.01 μF, depending on the signal source. Probe each filtered line to confirm that only required signals are present.

3. Probe each pc board to locate the areas of maximum radiation. Experiment with metal-foil tape to determine where a metal shield will be most effective. Install a temporary shield soldered to the ground plane to verify effectiveness.

4. You should examine purchased items such as disks and power supplies for I/O-line filters and radiation containment.

5. A commercially available filter or a suitable substitute should filter your circuit's input ac power line. Probe the ac-power input to check that any conducted interference is at least 20 dB below requirements.

6. Monitor your circuit's I/O lines during normal operation and track down any unexpected signals to their source. Again, any conducted interference should be at least 20 dB below requirements.

7. No matter how you measure the near-field radiation from your design, such radiation should be at least 20 dB below the 3-meter radiation limit. To make these measurements, you'll need a shielded, screened test room.

Thomas L Fischer
Pacific West Electronics
Costa Mesa, CA

## Protection diodes generate heat

Dear Bob:

You recommend using "antireversal" diodes across a

power supply's input to protect circuitry against reversal of the power supply's leads (See **Fig 4** on pg 126). However, if a power supply does get hooked up backwards, high currents will flow through the diodes, which might degrade or ruin them. Remember, the diodes *are* a part of the circuitry, too. Instead, I recommend connecting the diodes in series with the input pins **(Fig 4b)**.

Now, the board has protection but with virtually no diode current.

Marvin Smith
Harbor City, CA

Dear Mr Smith:

You are correct in some cases, and I guess I was delinquent in not mentioning them. For example, if you have a battery, putting the diode in series with the correct path may be appropriate. Then, if reversal happens, the battery won't be crowbarred and you will avoid damage to the battery and its environs. However, if you have a 5V bus, a diode in series with the supply would both waste a large fraction of the total voltage and possibly spoil the supply's regulation.

Even with a 15V supply, where the wasted power might be acceptable, the bounce and poor regulation of the supply might hurt the accuracy of the circuits that the supply powers. The diode's impedance may cause poor regulation. So, in cases where a regulator drives the power buses, the shunt antireversal diodes are a good idea. The solution presumes, of course, that the regulators are short-circuit proof.

The worst part of your circuit, Mr Smith, comes to light when one of the power-supply wires falls off or becomes disconnected. Then, the −14V bus could get pulled to 5 or 10V, depending on what loads are between the 14 and −14V buses. Many linear circuits can get very unhappy if fate pulls their negative-supply pin above ground. Even if the ICs didn't complain, the electrolytic power-supply bypass capacitors would be reverse-biased, a potentially destructive situation.

So, Mr Smith, would you agree that adding a couple additional antireversal rectifiers to your circuit would probably be a good idea?

Now, in what cases should designers *not* incorporate your series diodes without adding parallel antireversal diodes? The answer is low-voltage, high-current, or well-regulated applications.

Of course, you are correct that the rectifiers must be able to carry the short-circuit current of the regulator. Fortunately, 1N4002s are very inexpensive these days. Further, 1N5400s, which carry 3A, are only 19¢ each.

Best regards, and thank you for your comments. You are wise to "question authority."

RAP

Czar of Floobydust

PS: Whoops! Let's say you put diodes in series with your path, with a couple batteries for supplies. Now, if you short out the 14V buses, how can you be sure that your rectifier won't get ruined? Maybe you need to put a fuse in series with each diode? Maybe I ought to put a fuse in series with my supply buses? It just goes to show, things are not simple any more!

## So Bob, what do you think about solderless breadboards?

Here's a chunk of late-breaking floobydust—the topic is those solderless breadboards, which consist of a number of metal strips and solderless connectors hidden underneath a plastic panel with lots of holes in it. Schools often use them to introduce students to the joys of breadboarding because you can easily connect things by just stuffing wires and components into the holes. The problems begin with capacitance. The breadboards usually have 2, 3, or 5 pF between adjacent strips. On a good day, only a wise engineer could plan a layout that all the capacitors, sprinkled throughout the circuit, wouldn't ruin.

The next serious problem with solderless breadboards is the long leads, which make adding effective power-supply bypass capacitors close to a chip difficult.

Next, I suspect that some of these panels, although they are not inexpensive, use cheap plastics such as nylon. On a warm, humid day, cheap plastics do not offer high insulation resistance. Nobody wants to talk about what kind of plastic the breadboards are made of.

Finally, Mr Scott Bowman of Dublin, CA, points out that after you insert enough wires into any given hole, the solderless connector will scrape sufficient solder off the wire so that the scraps of solder will pile up and start to intermittently short out to an adjacent strip. Further, the adhesive that holds on the back panel tends to hold the solder scraps in place, so you can't clean the scraps out with a solvent or a blast of air.

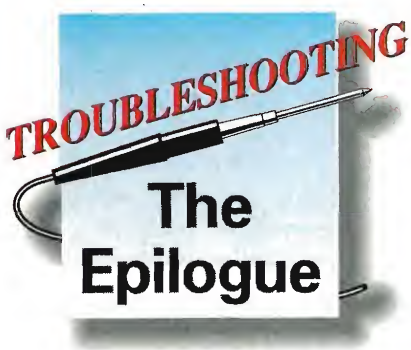
I didn't even think about these solderless breadboards when I wrote my series because I see them so rarely at work. They just have too many disadvantages to be good for any serious work. So, if you insist on using these slabs of trouble, you can't say I didn't warn you.

RAP

## The discrete charm of Popsicle sticks

Dear Bob:

To make component probes for debugging circuits, I glue capacitors or resistors on the ends of Popsicle sticks with epoxy. I keep the components' leads short—about ¼ in.—and cut at an angle to form precise contact points. Thus, you isolate your finger and body capacitance from the actual value of the component.




The Popsicle stick has a couple of advantages over simply grasping the component with your fingers or mounting it in a length of heat-shrink tubing. First, the Popsicle stick is more rigid than heat-shrink tubing. Second, the added length of the Popsicle stick often proves handy. I've got a whole box of capacitors and resistors mounted this way, which makes for a very efficient and portable trimming kit.

John Ardizzoni
M/A-COM
Lowell, MA

## Taking care of heat buildup

Dear Bob:

I use Tempilaq temperature-indicating paint from Tempil (South Plainfield, NJ) to monitor the temperature of power devices in metal cans and plastic packages, such as TO-220 devices. I use the paint both in development and in units shipped to the field.

The substance comes in various temperature grades. I anoint the top of each device with a range of paints. When and if a device heats up, each temperature-grade paint melts and fuses at a specific temperature, permanently altering the substance's appearance.

I also use the paint to ascertain the relative effectiveness of various thermally "conducting," insulating washers. These washers isolate a power device from its heat sink. I measure the time for the paste to change state after applying power to a device.

I discovered that silicon-based, elastomeric washers didn't work at all with TO-220 cases. The mounting screw of these cases is off center. One end of the case is tight, and the other is loose, which causes poor heat flow. I don't understand why these washers are even manufactured. Didn't the makers try one out before deciding to offer them?

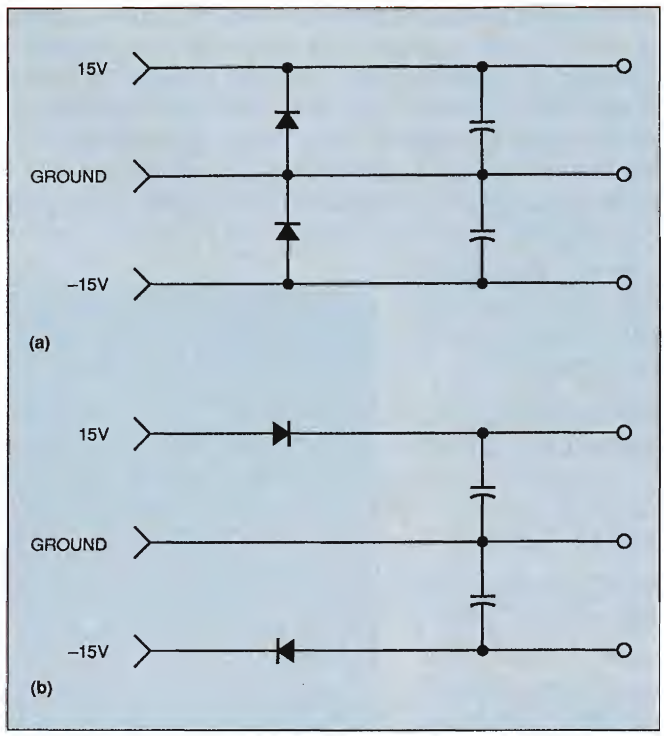



***Fig 4—Depending on your application,*** *you may want to connect antireversal diodes across* ***(a)*** *or in series* ***(b)*** *with a power supply's input pins.*

Washers aren't the only problem. One sample TO-220 device got hot so quickly that I performed a post mortem on it. I opened the package and pried the chip loose and observed that only about 15% of the die had been bonded to the substrate. Since that experience, I have steered clear of that particular manufacturer.

Bill Sturgeon
Sturgeon Engineering Co
Petrollia, CA

Dear Mr Sturgeon:

Thanks for your tip. Most of the guys in our lab don't use Tempilaq, but it's a good tip. We use thermocouples on the can or diodes in the chip.

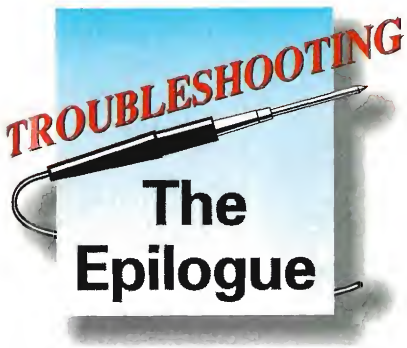
RAP

## Another reason to distrust computers

Dear Bob:

You're right. Most people, even technical people who should know better, tend to treat any numeric display or computer readout as if it were engraved in stone, ignoring whatever imperfect mechanism generated digits. They're even in awe of numbers scratched in Jello.

Back in the sixties, there was a story circulating about the Apprentice Engineer who had been experimenting with the plant's new analog computer. He ran up to the Chief Engineer waving a sheaf of printouts. "Look," he said excitedly, "I've come up with a simulation of our power-plant heating and air-conditioning system that will double the plant's efficiency!" The Chief Engineer studied the printout for a few moments. "Yes," he said, "but look here." And he pointed to the flow diagram, "This 17°F water is going to be awfully hard on the pumps."




Your frustration with the menu burden of these wonderful new instruments is right on target. One thing that I detest intensely and that seems to occur with increasing frequency is staring blankly at a screen or cursor, knowing full well that the reason it obstinately refuses to do your bidding is almost certainly a consequence of your imperfect understanding of its menus and possibly also of your failure to read the manual all the way through—which you'll do the next time you have a spare week. Keep up the good work.

Reginald W Neale
Connoisseur of Solder Globs
Rochester, NY

## Diode-connected confusion clears

Dear Bob:

I'm really confused by your apology on page 34 of the November 23, 1989, issue of EDN. I understand about diode-connected transistors; we use them often. However, we connect the base to the emitter and thereby use the base-collector junction. The breakdown voltage of such a connection is typically about the same as the transistor's maximum $V_{CE}$ rating. If we use your method, the breakdown rating will be only 5 to 7V typ, according to data sheets. I usually want more.

John Paul Hoffman
Caterpillar Inc
Peoria, IL

**So Bob, what do you think about spreadsheets?**

Normally, I hate, despise, and detest using spreadsheets for linear-circuit design. They give you an answer, but they don't give you much feel for what is important.

Dear Mr Hoffman:

You're right, the collector-emitter junction can handle more current than the base-emitter junction, but it's also slower.

RAP

## Hobbyist learns about life

Dear Bob:

A few years ago, when I first moved into a new house and hooked up my stereo, the left channel decided to fry the output transistors. The power amp had heavy feedback and was a standard design running class A or AB. It had a "tweak" for nulling out standing current in the output stage. I found that as I monitored and increased the standing current in the left channel, the left stage would run away at a standing-current value, which the right channel could handle with no problem.

Now I was confused. I had two identical circuits, one of which was fine and the other of which wouldn't tweak up to spec. I noticed that if I was probing certain nodes in the left channel with my scope, the left channel wouldn't run away. The scope didn't show anything abnormal, but I suspected that something was causing the circuit to oscillate.

Now—one very important detail: My new house was two blocks from the top of a hill covered with an antenna farm—including an AM broadcast station at 970 kHz. The bandwidth of my stereo's power amp was well over 1 MHz. I discovered that if I hung a 0.1-μF capacitor from both sides of the power-line entrance to chassis ground, everything was fine. EMI was coming down the power line causing the circuit to break into destructive oscillation. I couldn't see the oscillation on the scope because the scope's ground lead shunted the EMI to power-line ground.

I learned that

1. Identical circuits aren't necessarily.
2. Marginal designs that work on the bench may fail when put into service.
3. Look for clues anywhere.

Thanks again for some great articles!

Steve Coffman
TSSI
Beaverton, OR

Dear Mr Coffman:

I think you forgot a fourth point:

4. If some bandwidth is good and some more bandwidth is better, then lots and lots of bandwidth is not best—it may just be a disaster! Giving a power amplifier lots and lots of bandwidth is one good way to buy trouble. But I find it interesting that the 970-kHz EMI came in on the power line and not on the speaker cables.

RAP

## The troubleshooting series at a glance

Part 1—"Troubleshooting is more effective with the right philosophy," *EDN*, January 5, 1989, pg 147.

Part 2—"The right equipment is essential for effective troubleshooting," *EDN*, January 19, 1989, pg 166.

Part 3—"Troubleshooting gets down to the component level," *EDN*, February 2, 1989, pg 175.

Part 4—"A knowledge of capacitor subtleties helps solve capacitor-based troubles," *EDN*, February 16, 1989, pg 127.

Part 5—"Follow simple rules to prevent material and assembly problems" *EDN*, March 2, 1989, pg 159.

Part 6—"Active-component problems yield to painstaking probing," *EDN*, August 3, 1989, pg 127.

Part 7—"Rely on semiconductor basics to identify transistor problems," *EDN*, August 17, 1989, pg 129.

Part 8—"Keep a broad outlook when troubleshooting op-amp circuits," *EDN*, September 1, 1989, pg 131.

Part 9—"Troubleshooting techniques quash spurious oscillations," *EDN*, September 14, 1989, pg 151.

Part 10—"The analog/digital boundary needn't be a never-never land," *EDN*, September 28, 1989, pg 145.

Part 11—"Preside over power components with design expertise," *EDN*, October 12, 1989, pg 177.

Part 12—"Troubleshooting series comes to a close," *EDN*, October 26, 1989, pg 171.

Bob Pease illustration by Bruce Gilfoy

**Article Interest Quotient (Circle One)**
**High 488 Medium 489 Low 490**